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Tai et al.

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(54) **BI-DIRECTIONAL ISOLATOR**

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(22) Filed: **Aug. 16, 2001**

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Related U.S. Application Data

(63) Continuation-in-part of application No. 09/645,862, filed on Aug. 24, 2000, now abandoned, and a continuation-in-part of application No. 09/558,848, filed on Apr. 27, 2000, now abandoned, which is a continuation-in-part of application No. 09/377,692, filed on Aug. 20, 1999, now Pat. No. 6,268,954.

(51) **Int. Cl.**^{7} **G02B 5/30**

(52) **U.S. Cl.** **359/484**; 359/494; 359/495; 359/497; 372/337.1; 372/341.3; 372/703

(58) **Field of Search** 359/484, 494, 359/495, 497; 372/337.1, 341.3, 703

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,459,528 B1 * 10/2002 Cao 359/341.2

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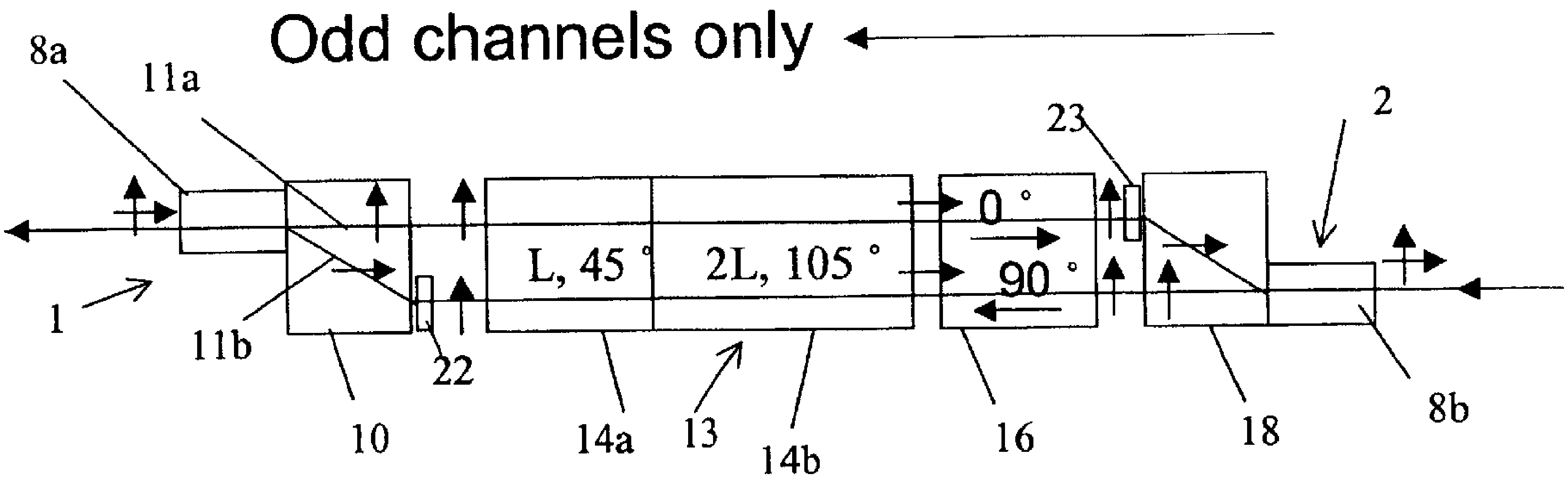
Primary Examiner—Audrey Chang
Assistant Examiner—Craig Curtis
(74) *Attorney, Agent, or Firm*—Hall, Priddy, Myers & Vande Sande

(57) **ABSTRACT**

Bi-directional wavelength interleaving optical isolators provide the ability to pass a first set of optical signals (e.g., ITU even channels) from a first port to a second port, while preventing a second set of optical signals from passing thereto. The bi-directional wavelength interleaving optical isolators also pass the second set of optical signals (e.g., ITU odd channels) from the second port to the first port, while preventing the first set of optical signals from passing thereto. Thus, the bi-directional wavelength interleaving optical isolator can provide bi-directional communications by passing a first set of signals in a first direction and a second set of signals in a second direction.

20 Claims, 16 Drawing Sheets



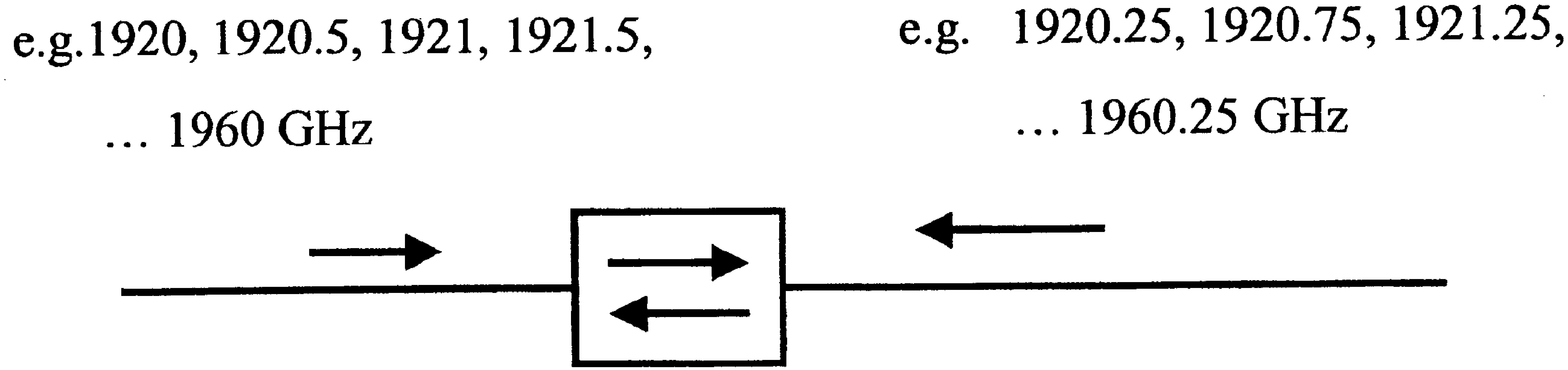
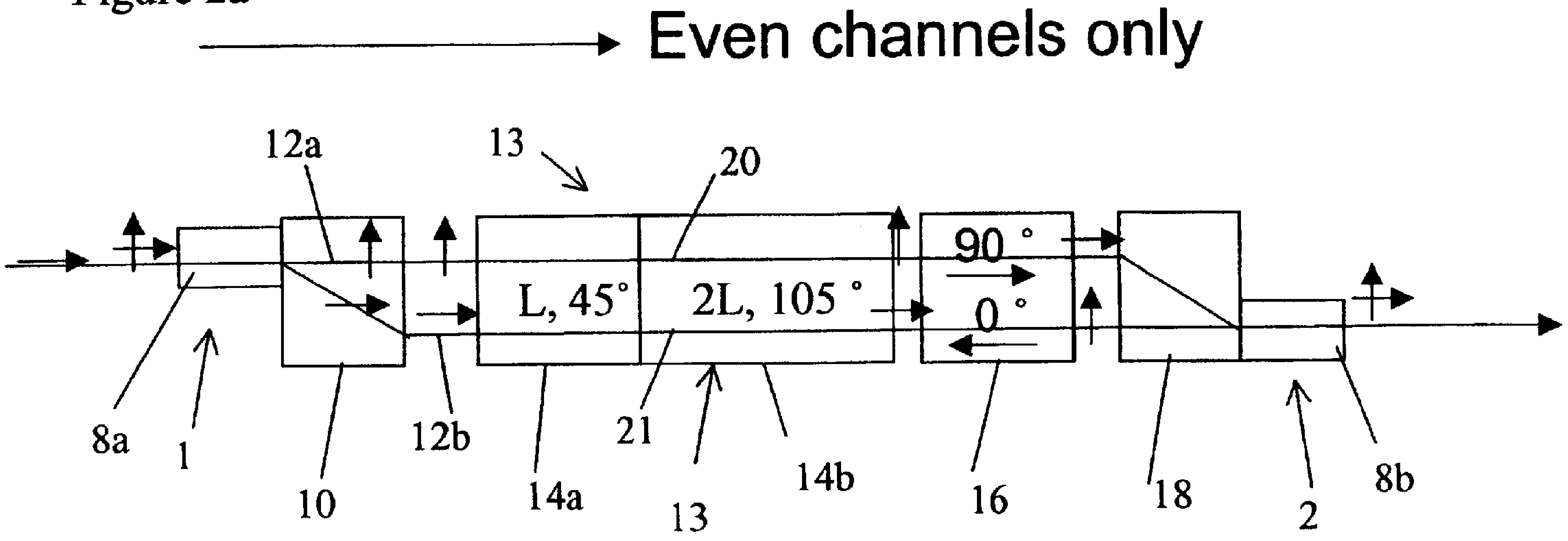

e.g.1920, 1920.5, 1921, 1921.5,
… 1960 GHz
e.g. 1920.25, 1920.75, 1921.25,
… 1960.25 GHz

Fig. 1

Figure 2a



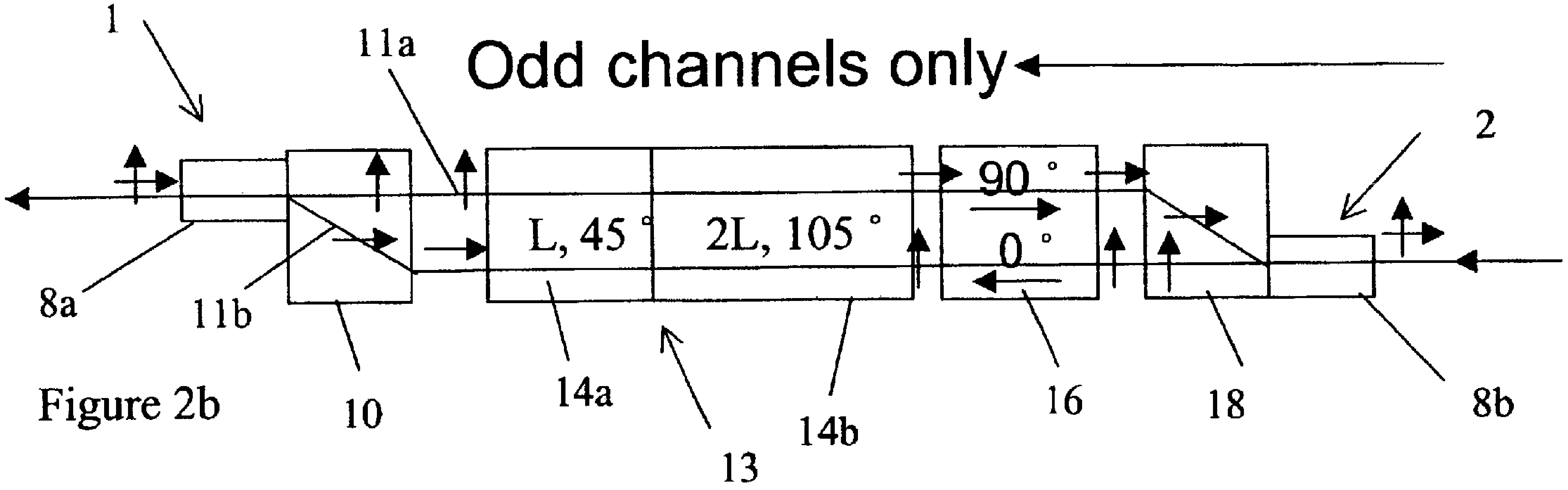
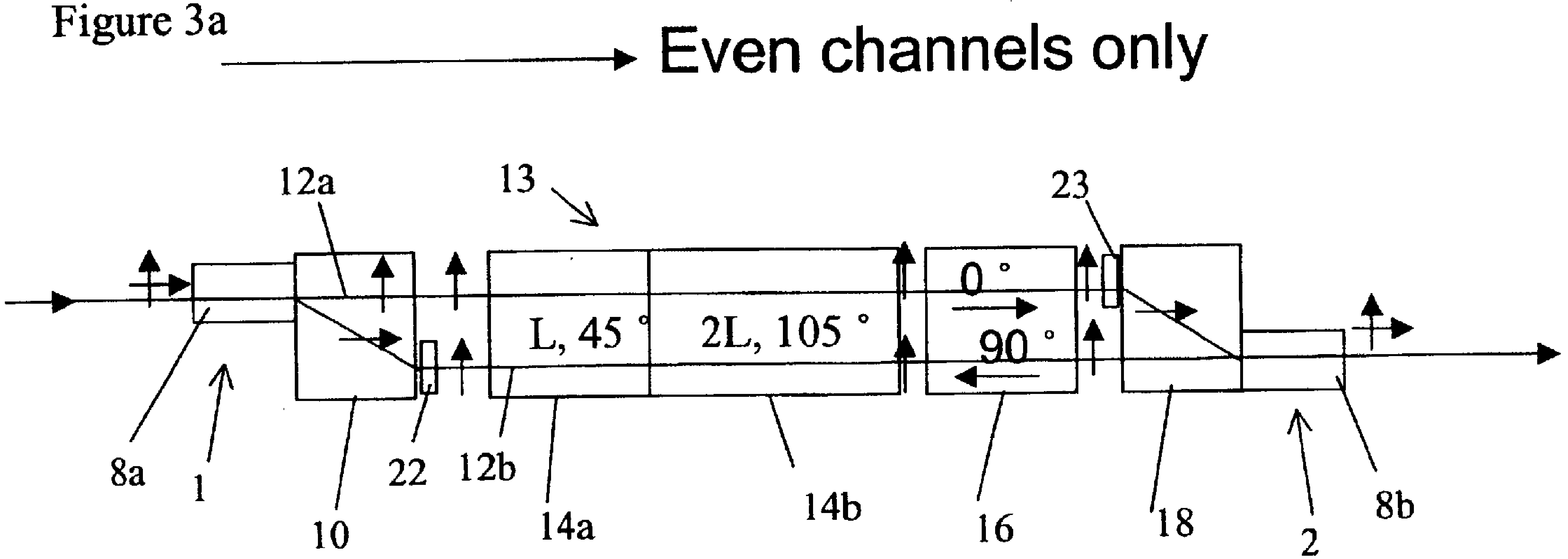


Figure 2b

Figure 3a



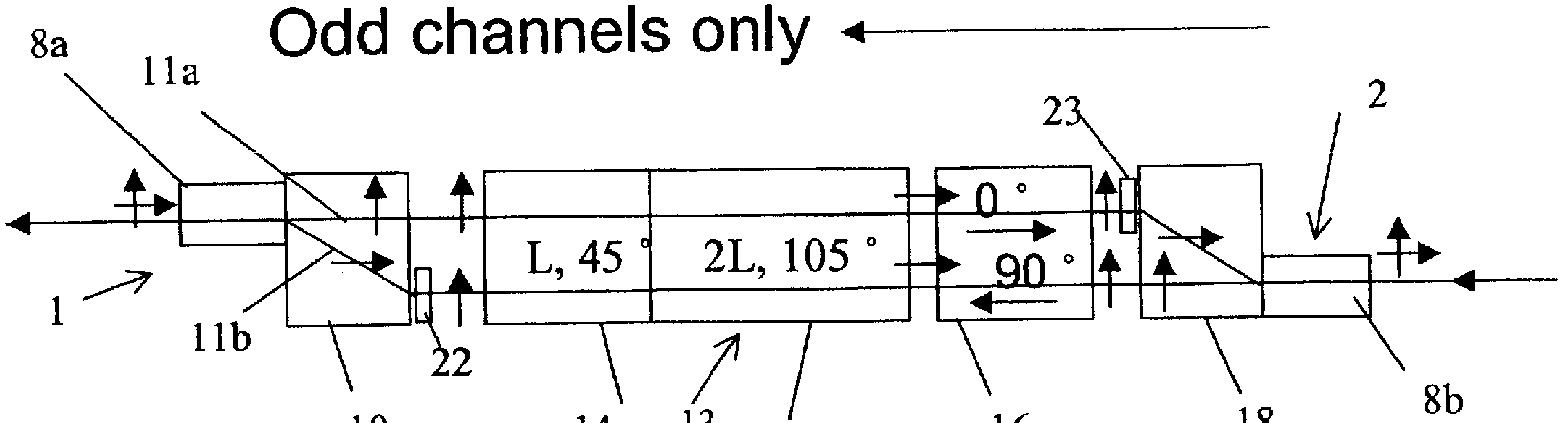
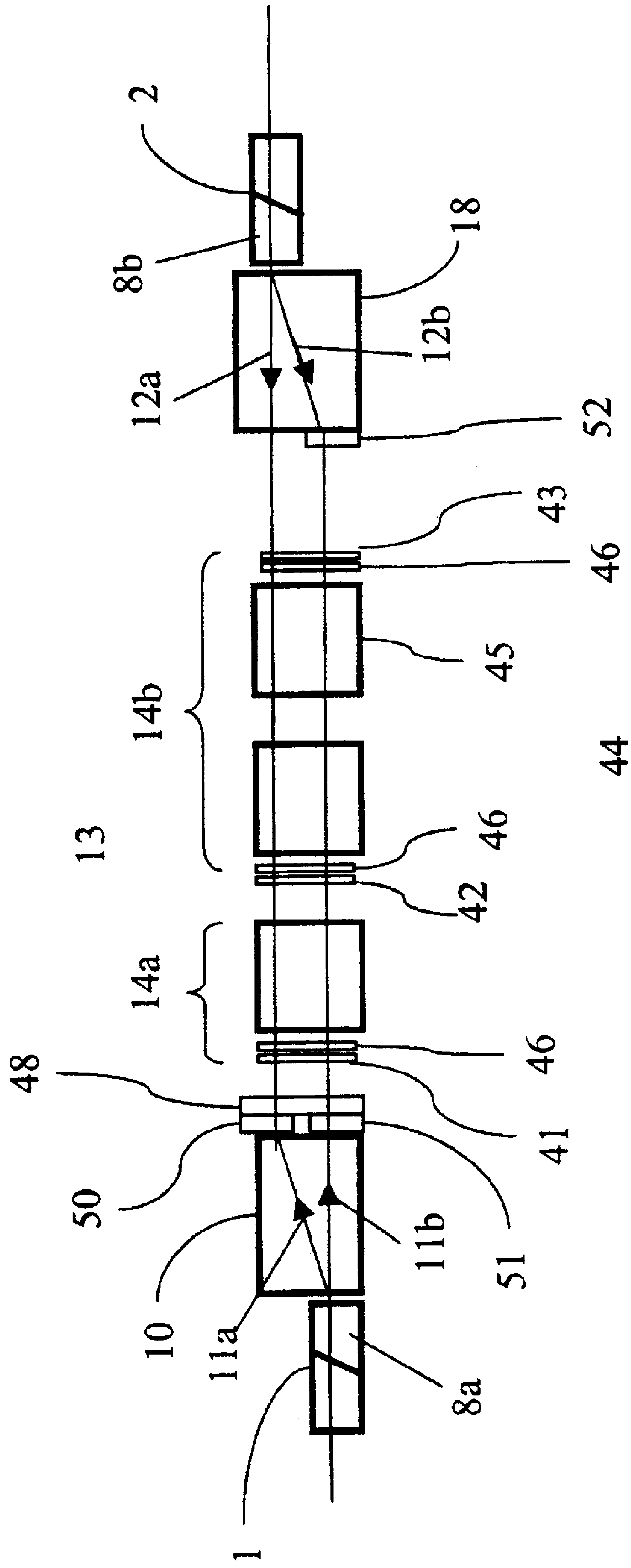


Figure 3b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12b
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14b
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14a
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11b
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11a
8a
1

Fig. 4

Fig. 5

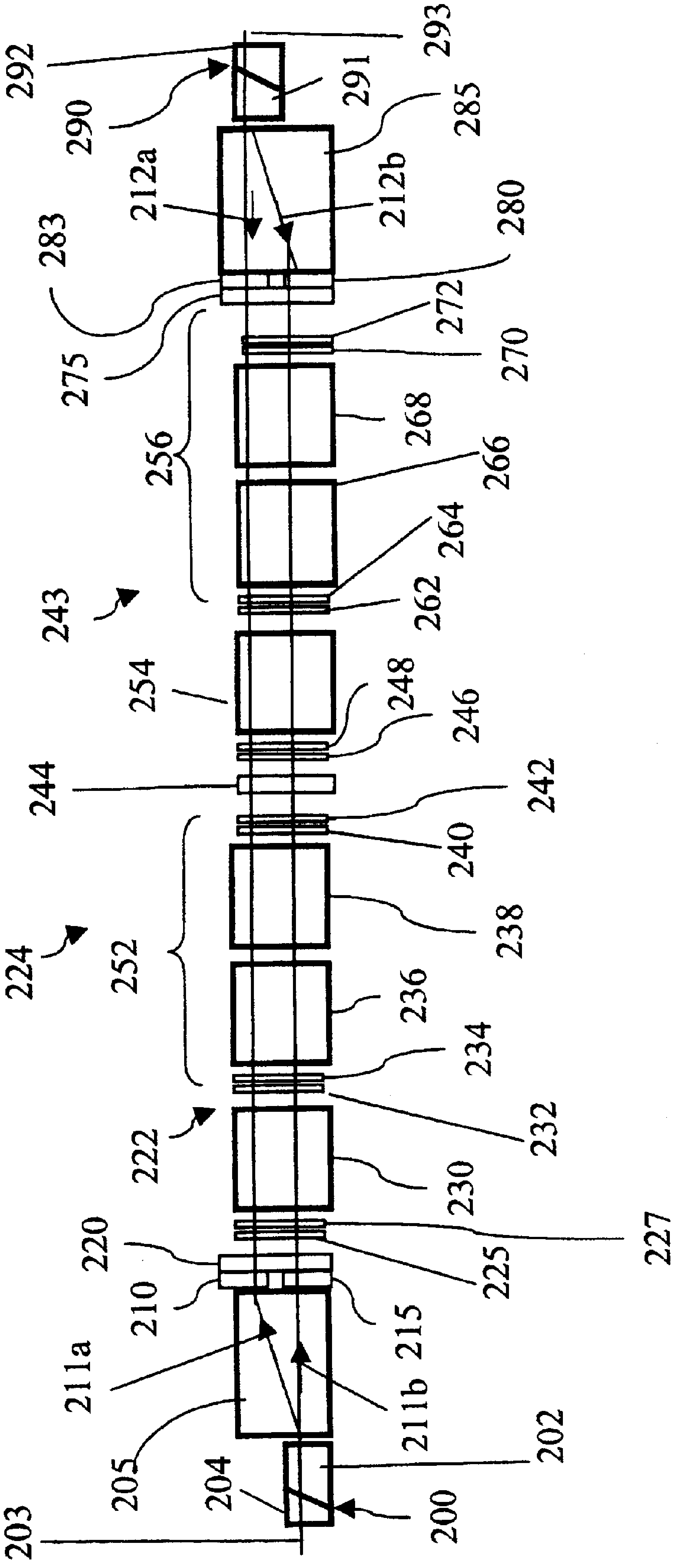
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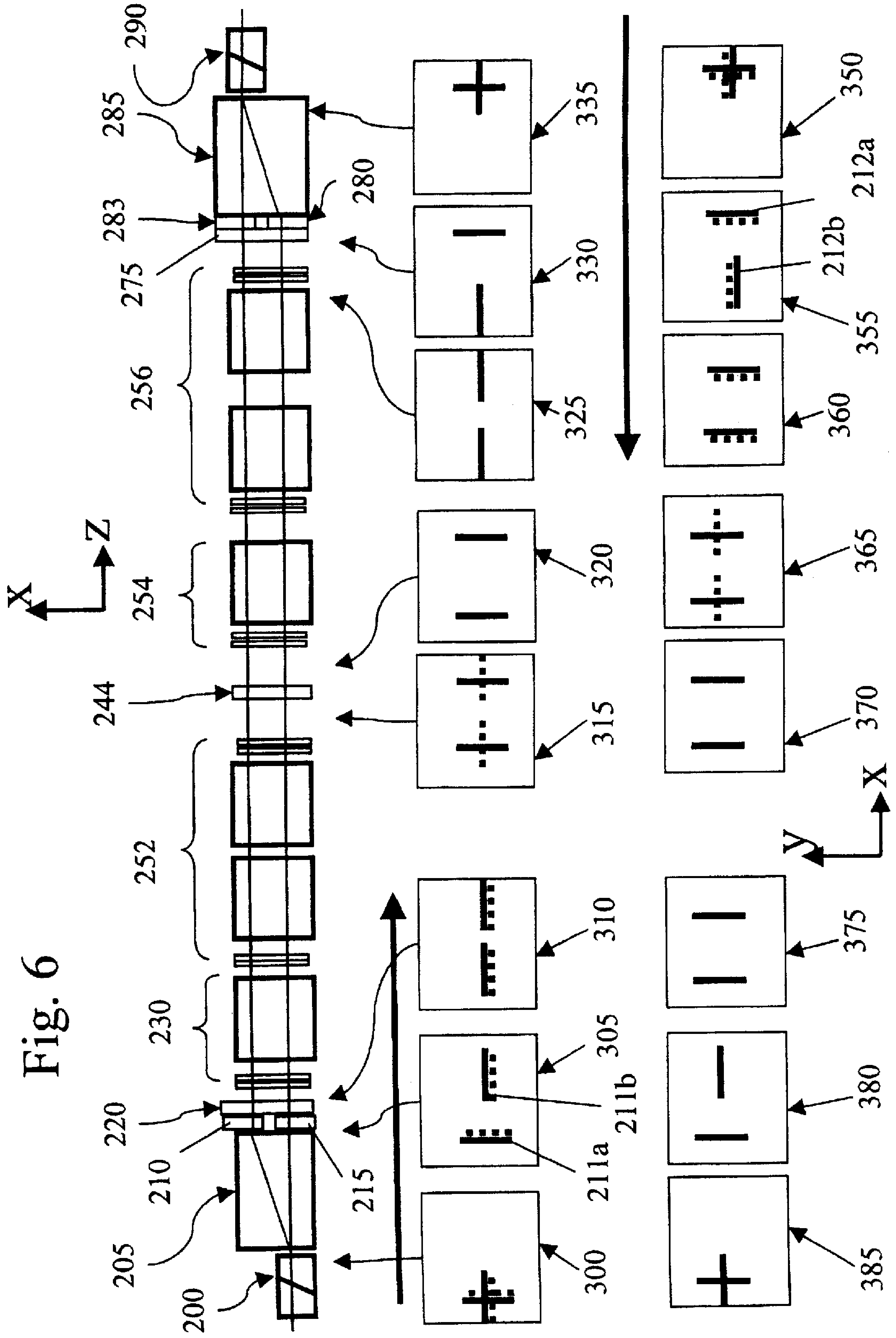
Fig. 6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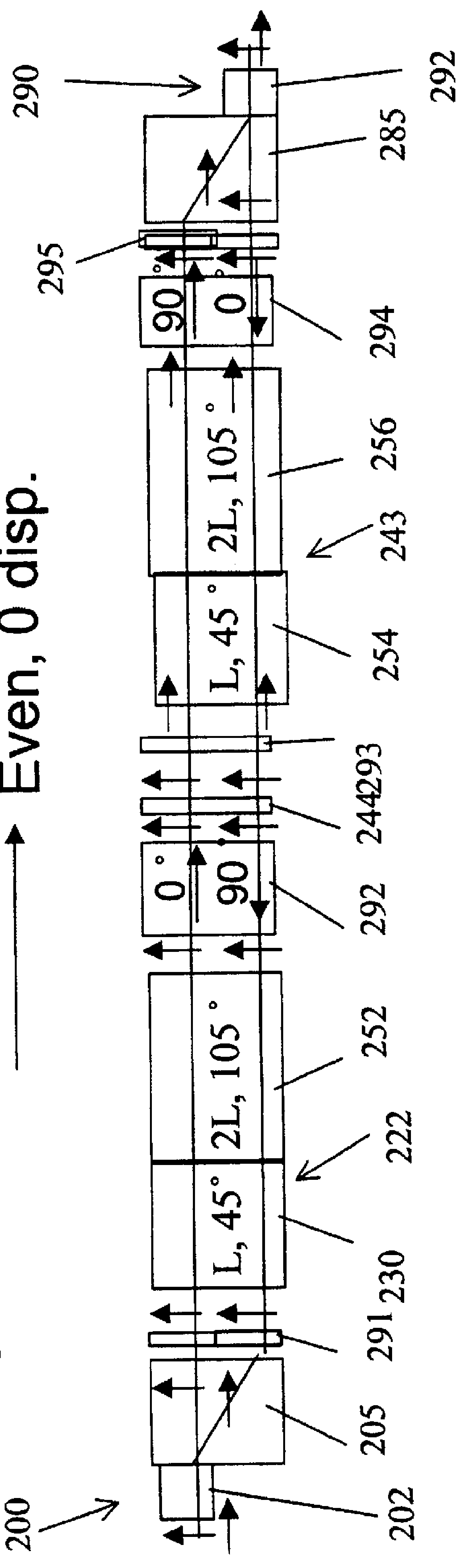

Figure 7a

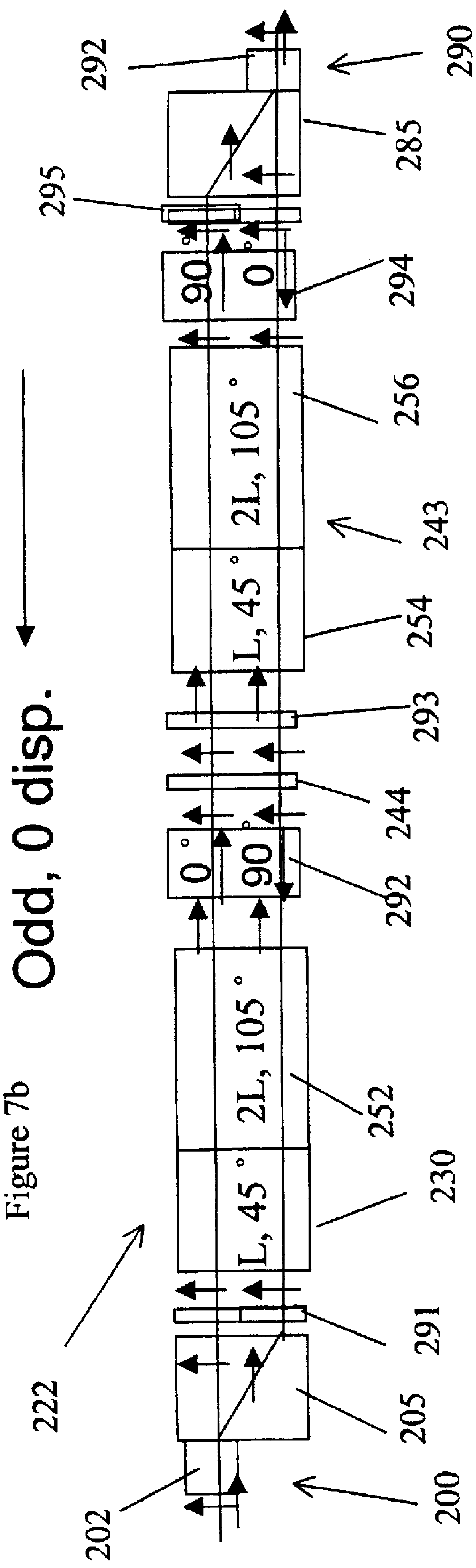

Figure 7b

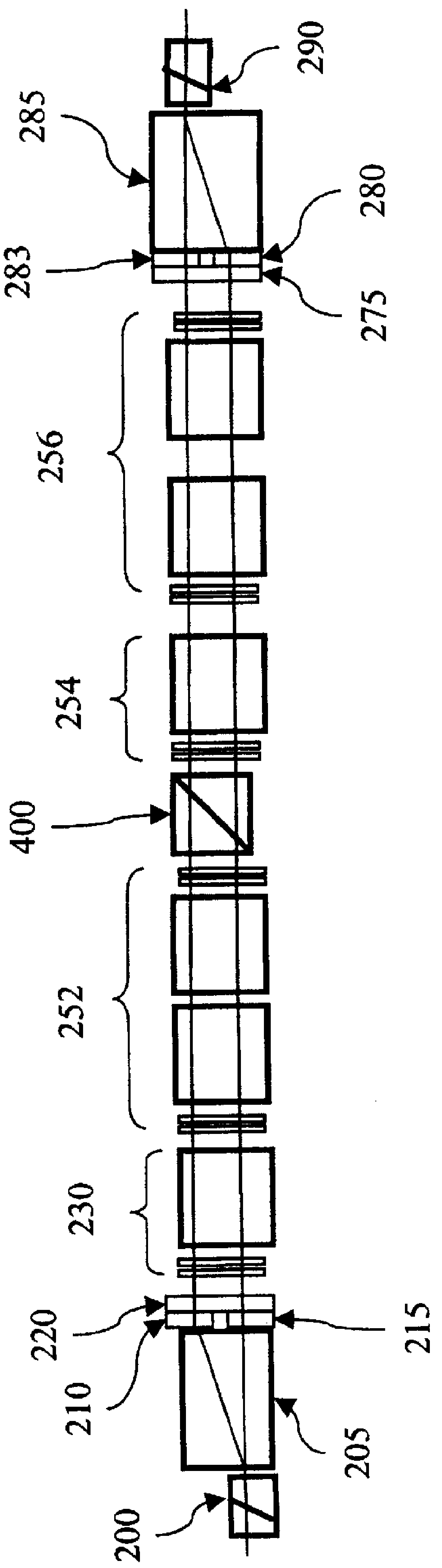
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Fig. 8

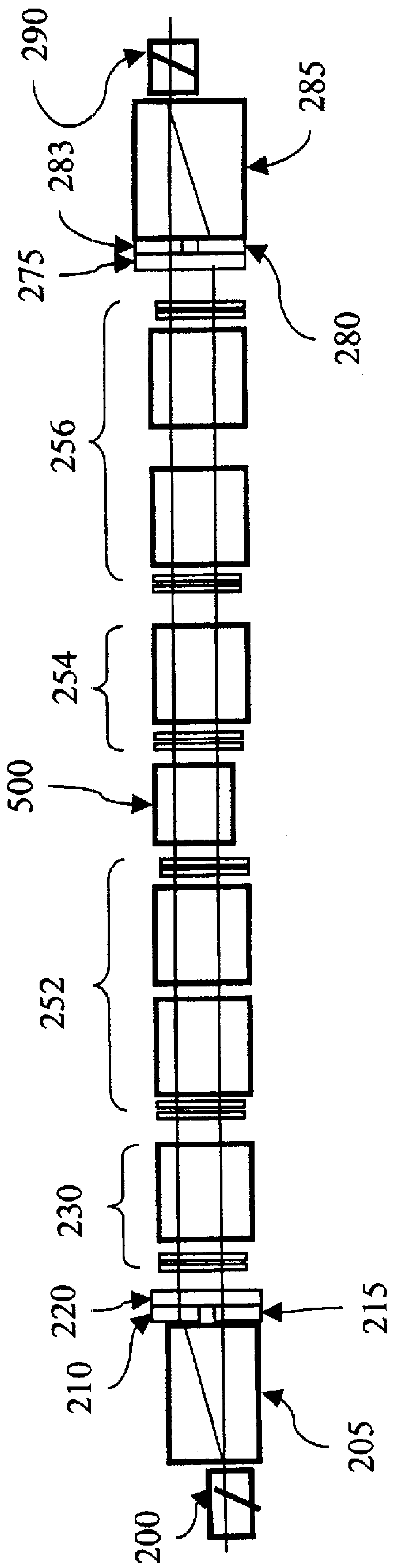
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Fig. 9

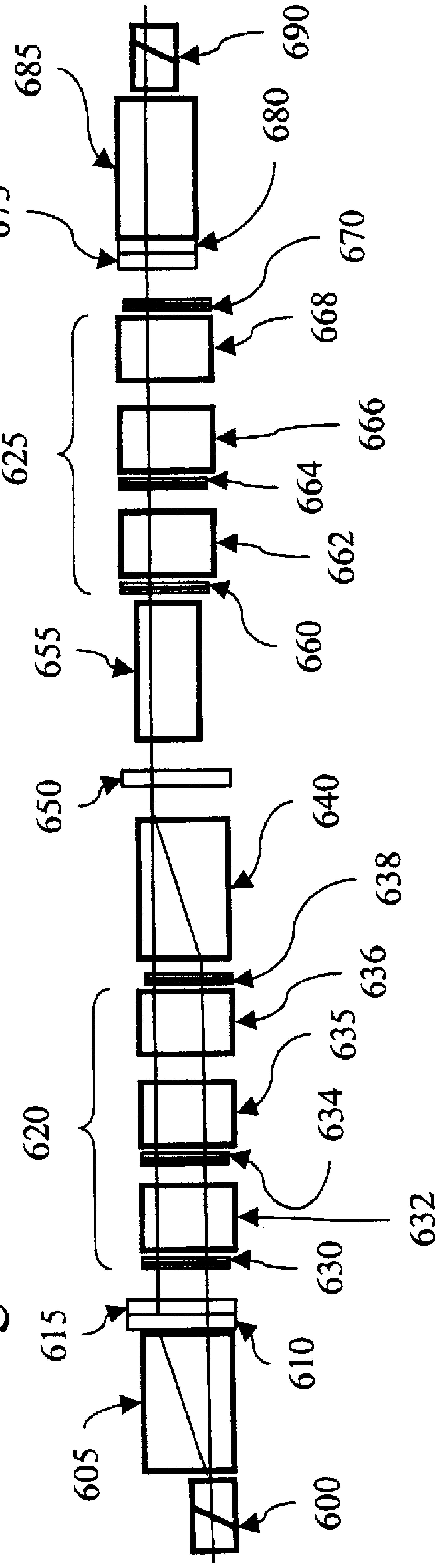


Fig. 10a

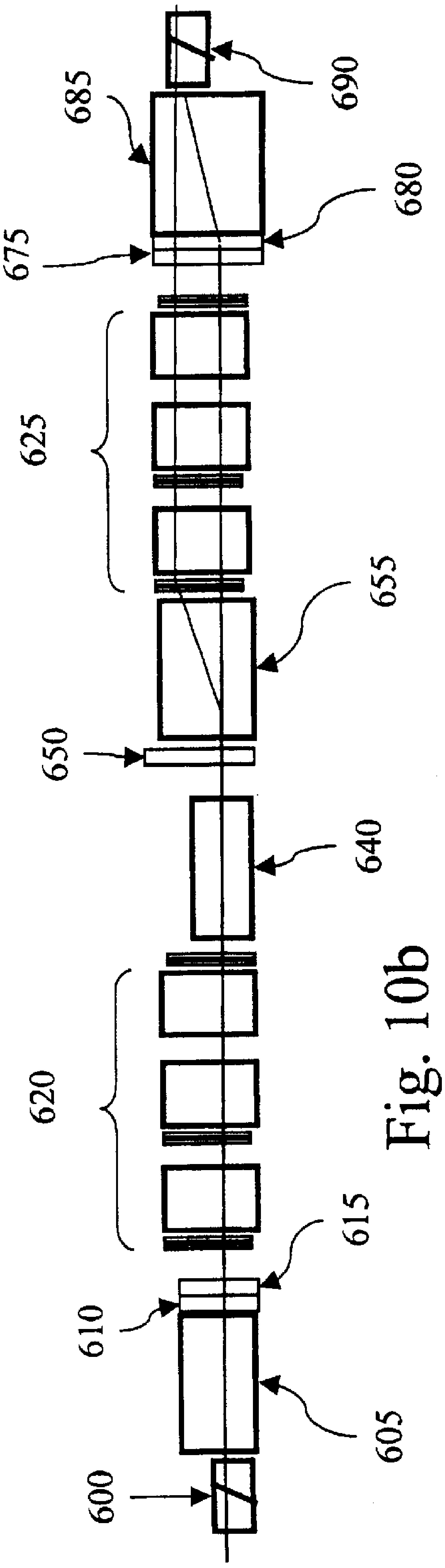
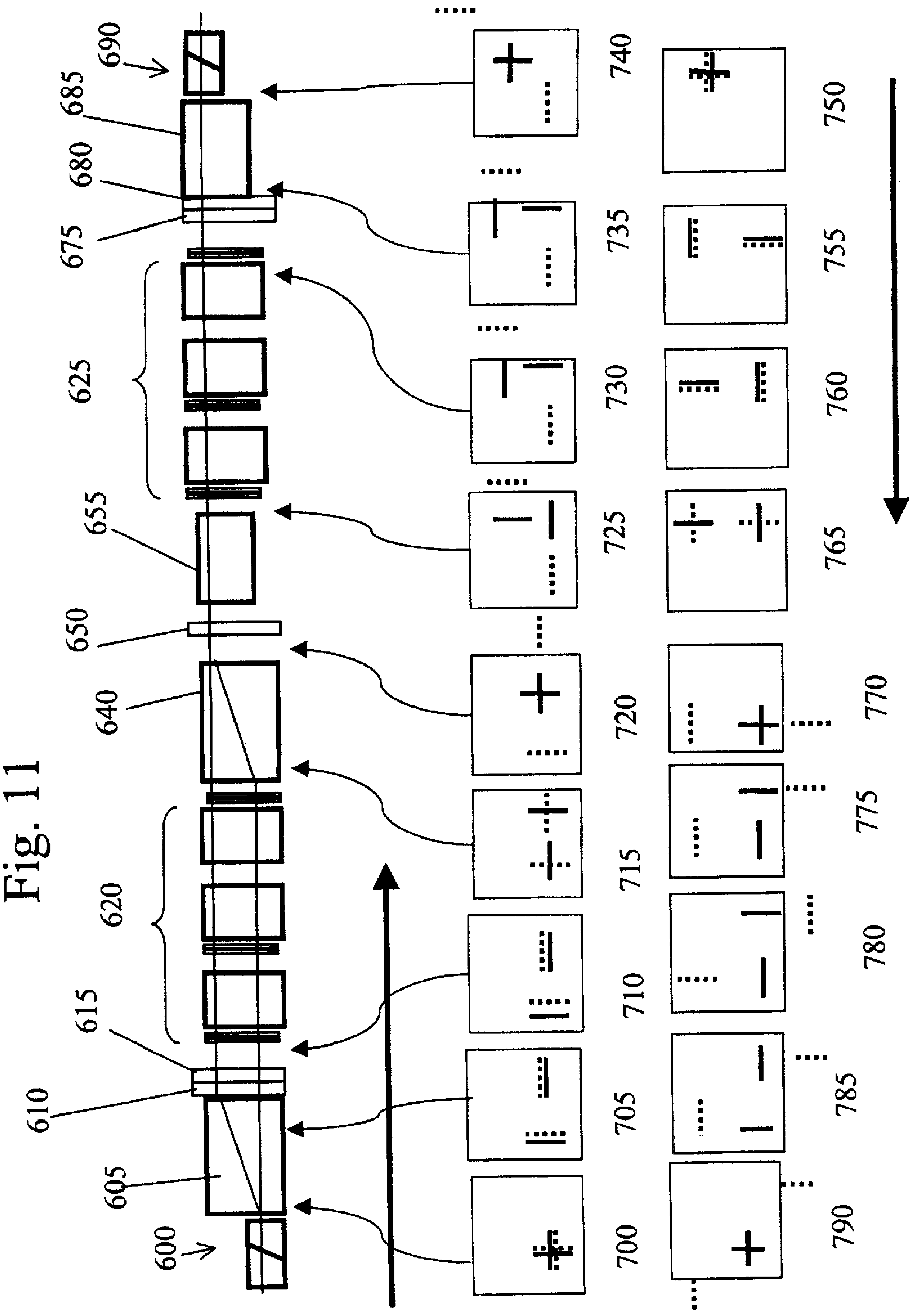


Fig. 10b

Fig. 11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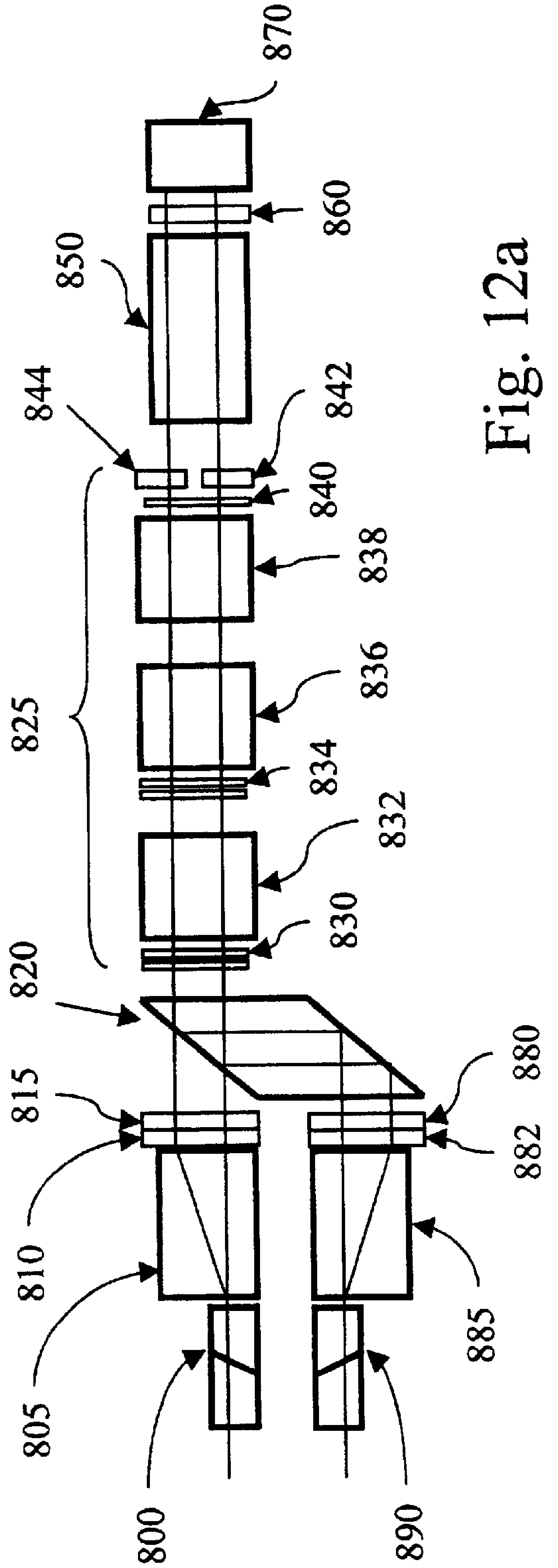


Fig. 12a

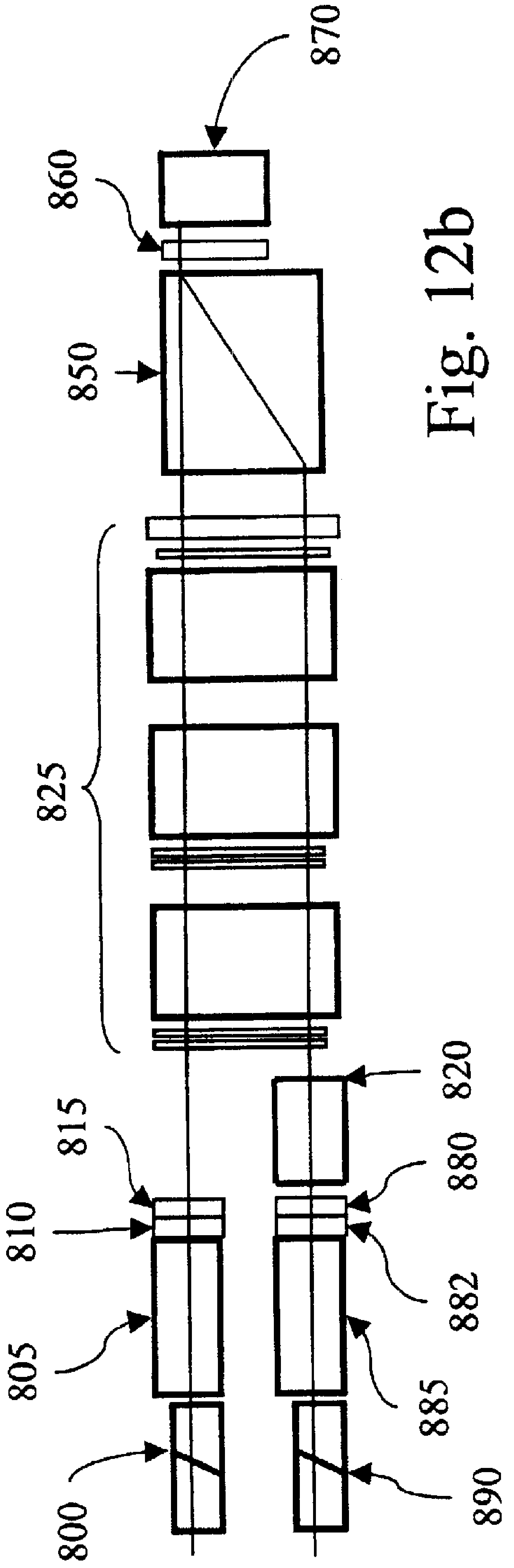


Fig. 12b

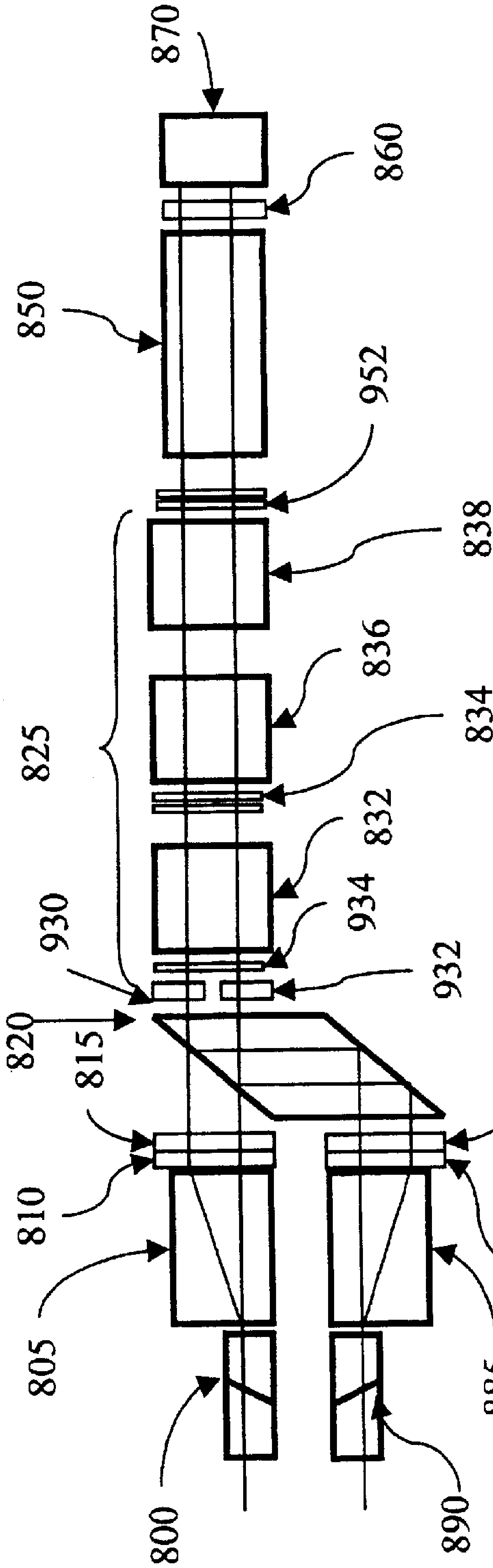


Fig. 13a

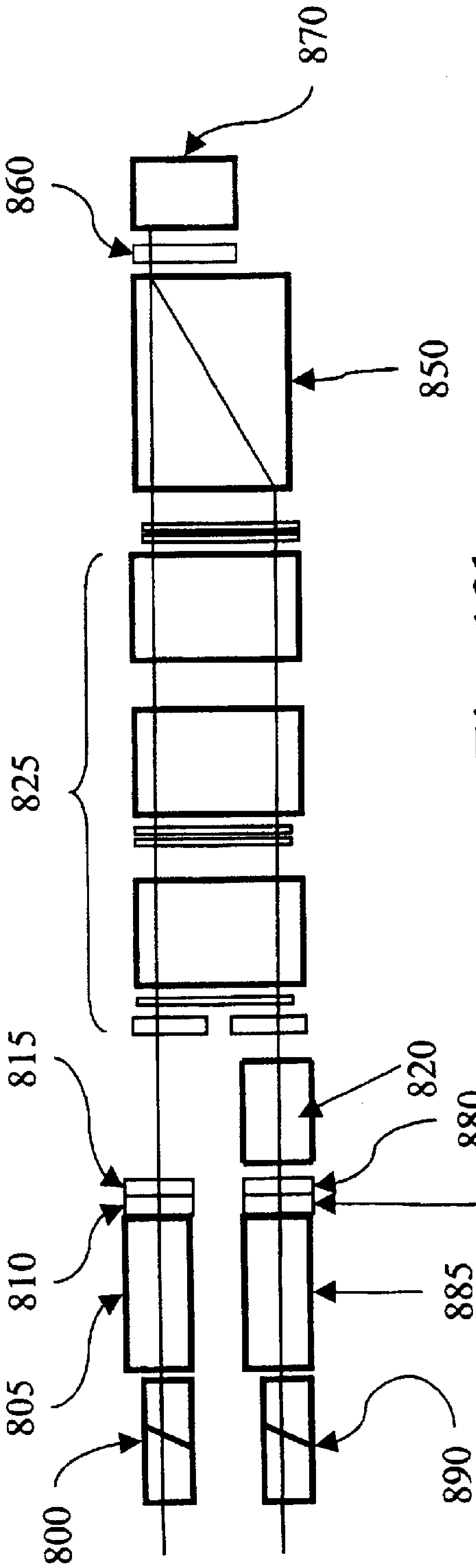


Fig. 13b

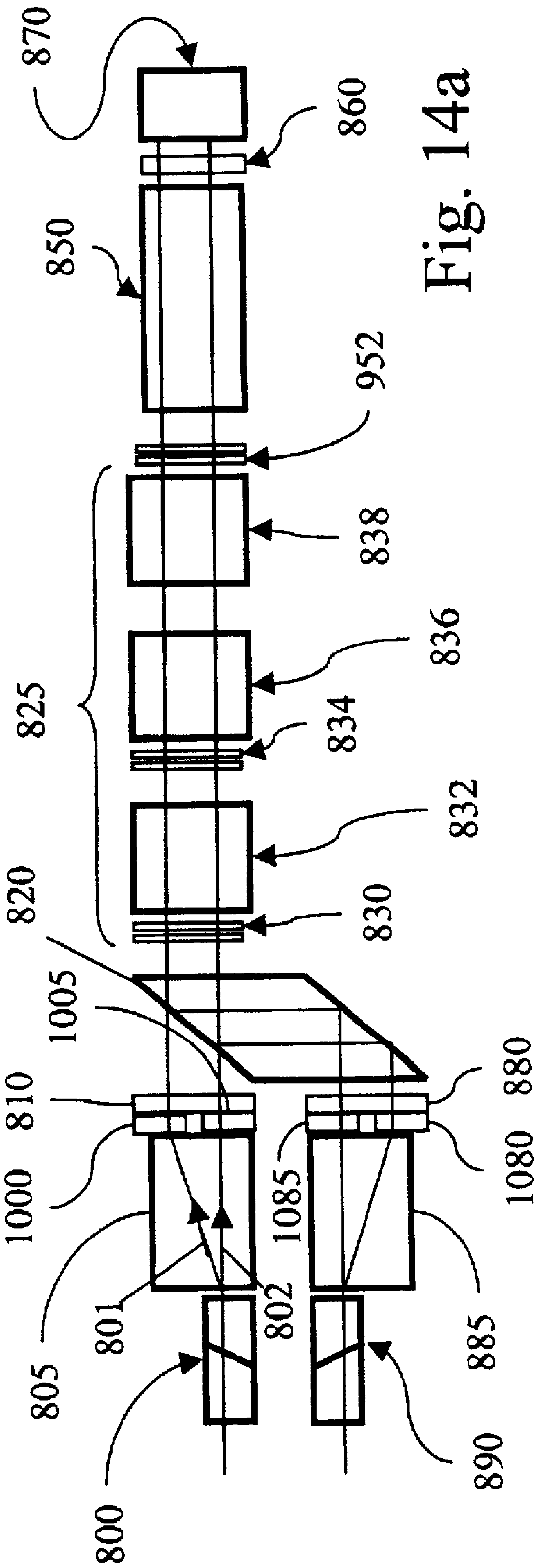


Fig. 14a

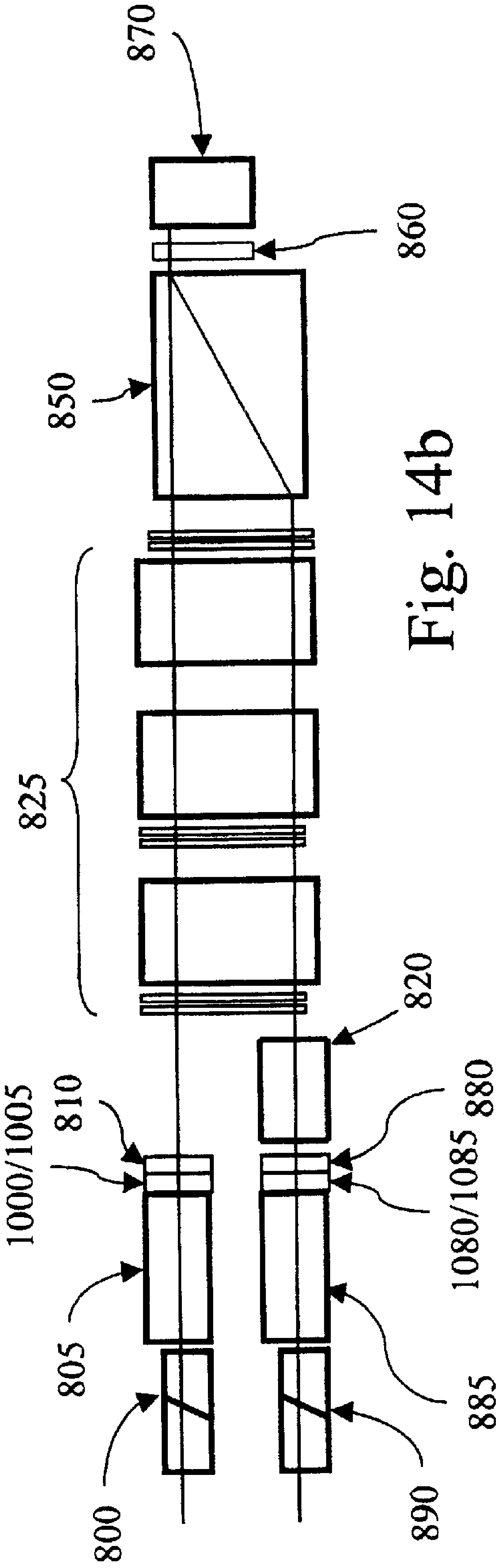


Fig. 14b

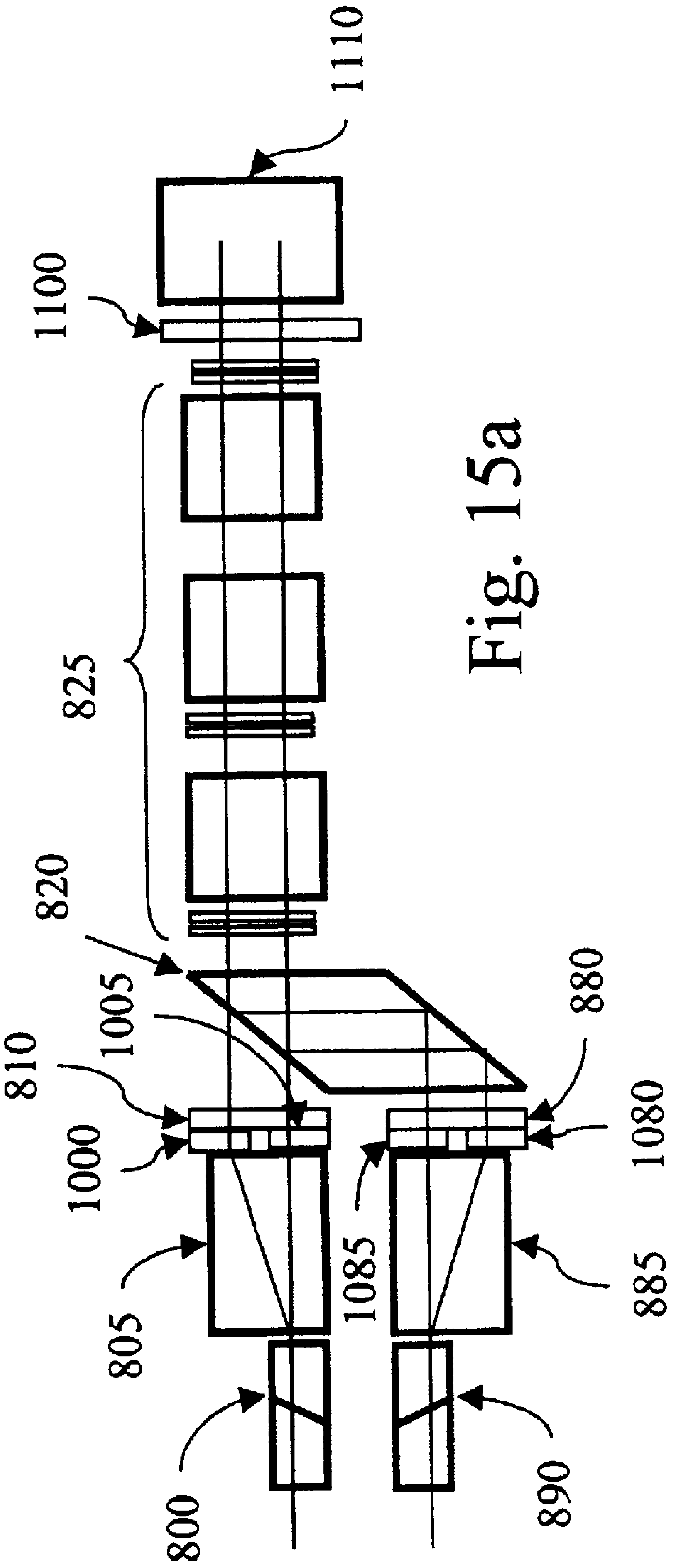


Fig. 15a

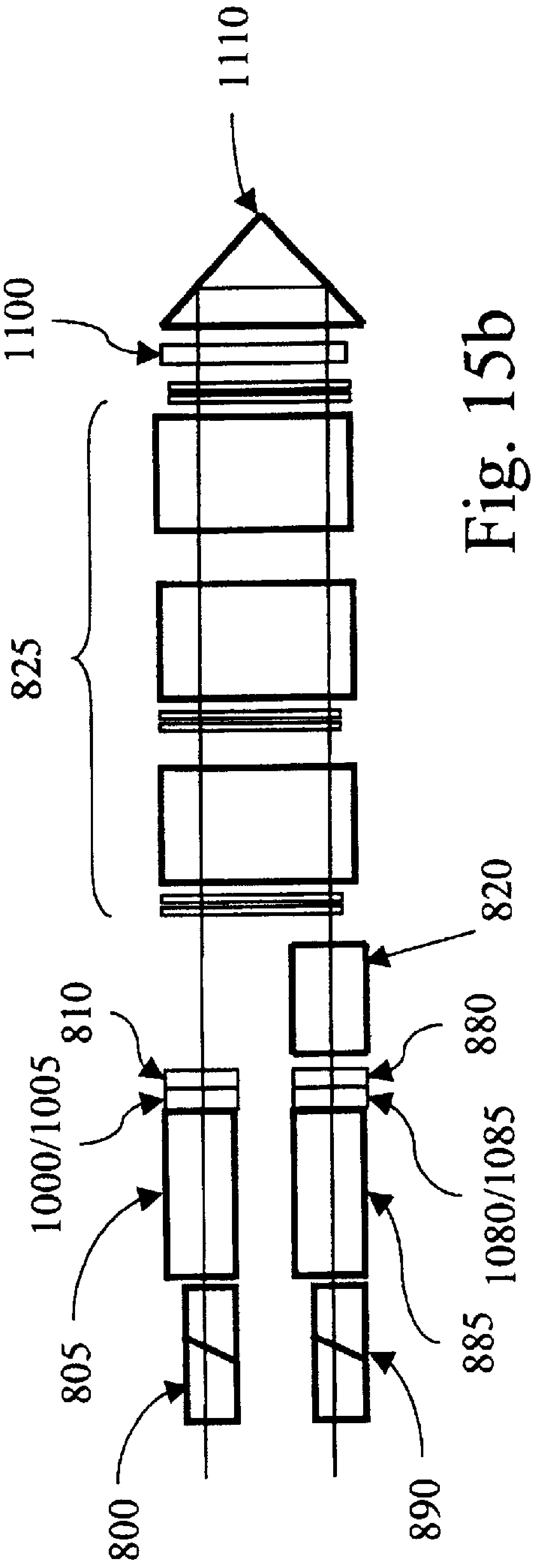
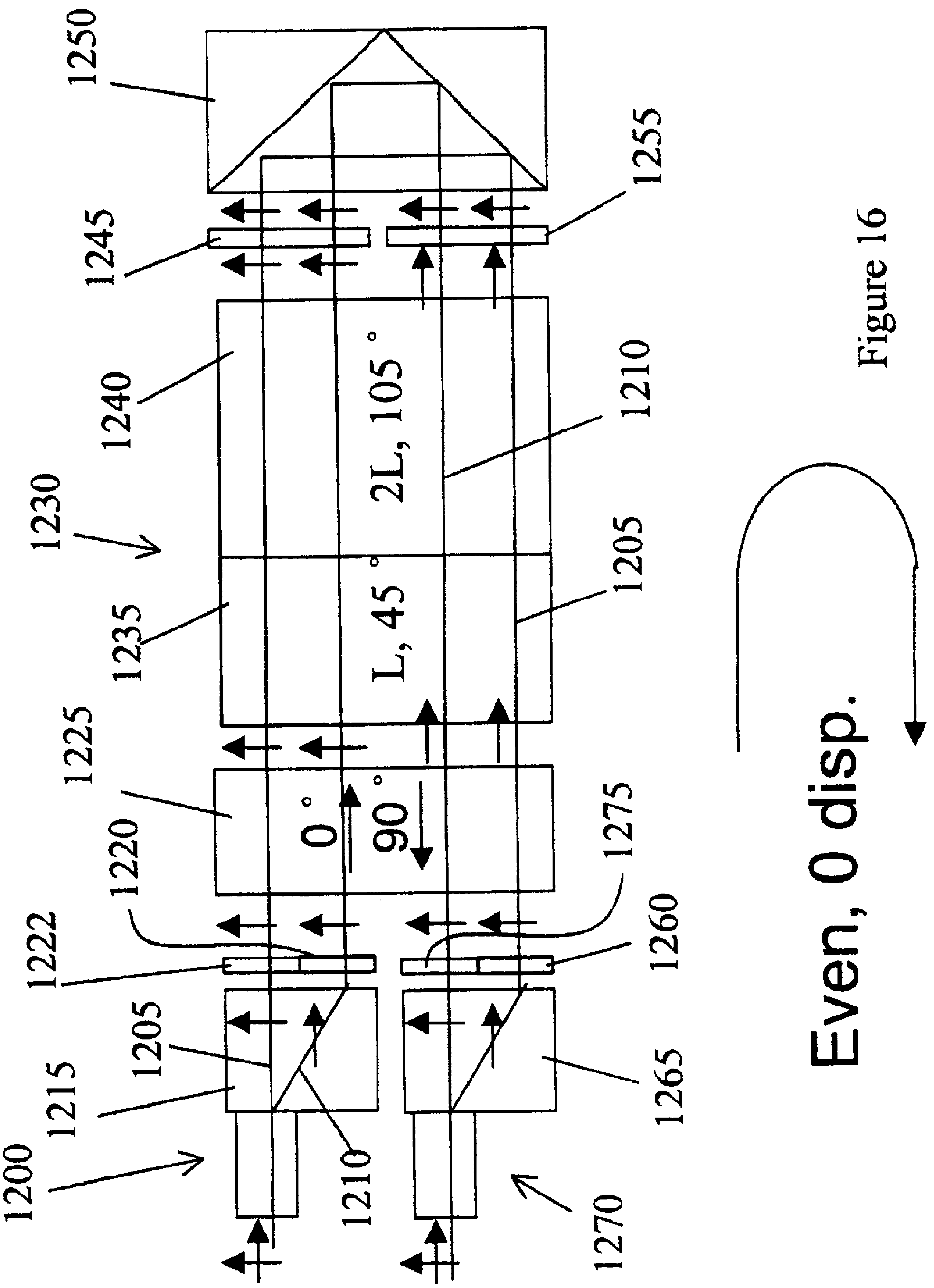


Fig. 15b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1215
1205
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0°
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1230
1235
L, 45°
2L, 105°
1240
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1250
1255
1210
1205
1275
1260
1265
1270
Even, 0 disp.

Figure 16

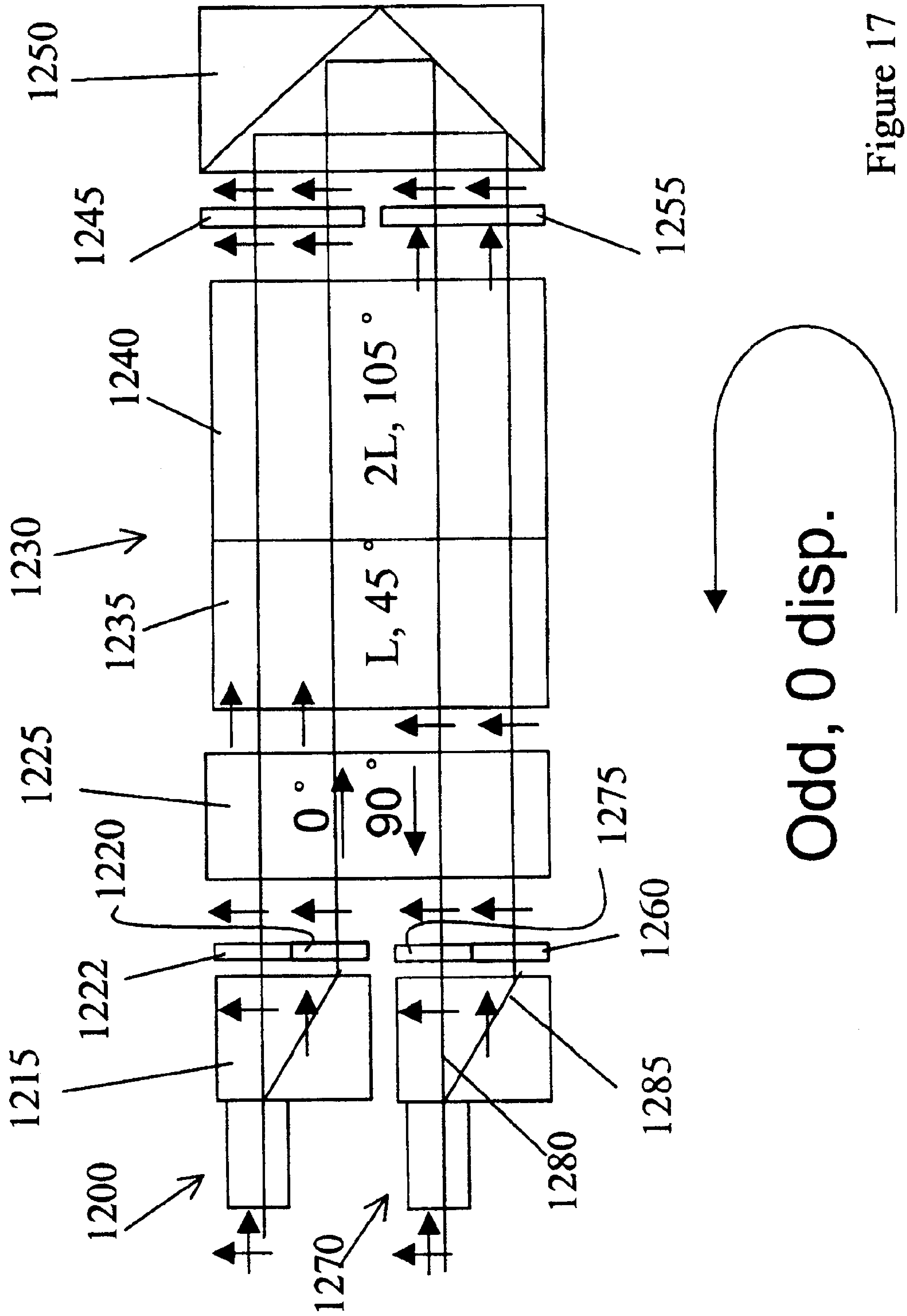
1250
1245
1255
1240
2L, 105 °
1230
1235
L, 45 °
1225
0 °
90 °
1220
1275
1260
1222
1215
1285
1280
1200
1270
Odd, 0 disp.

Figure 17

BI-DIRECTIONAL ISOLATOR

RELATED APPLICATIONS

This application is a continuation-in-part of application Ser. No. 09/645,862 filed Aug. 24, 2000, and now abandoned; and is also a continuation-in-part of application Ser. No. 09/558,848 filed Apr. 27, 2000, and now abandoned, which in turn is a continuation-in-part of application Ser. No. 09/377,692, therewith, filed Aug. 20, 1999 and now U.S. Pat. No. 6,268,954 issued Jul. 31, 2001.

The present U.S. patent application is related to the following U.S. patent applications:

(1) Bi-Directional Optical Circulators filed Aug. 24, 2000 and having application Ser. No. 09/645,863 and

(2) Wavelength Interleaving Cross-Connects filed Aug. 24, 2000 and having application Ser. No. 09/645,459.

FIELD OF THE INVENTION

The invention relates to optical isolators, and in particular to bi-directional optical isolators having a first comb filter response in a first direction through the device, which is different from a second comb filter response in a second opposite direction through the device.

BACKGROUND OF THE INVENTION

An optical isolator is a device intended to prevent return reflections along a transmission path. Isolators are commonly used optical components that can be used, for example, to prevent reflections in an optical fiber from interfering with the transfer of signals. Current isolators are uni-directional devices that allow optical signals to pass in one direction and not to pass in the opposite direction.

To provide a functional bi-directional optical system, uni-directional isolators are used for transmission in each direction. Requiring isolator sets for each direction increases the cost and complexity of an optical network in which bi-directional isolation is required. Therefore, it is desirable to provide a bi-directional optical isolator.

One prior art polarization independent optical isolator is described in U.S. Pat. No. 5,033,830 entitled Polarization Independent Optical Isolator, issued Jul. 23, 1991 in the name of Jameson. Jameson describes an isolator having a single birefringent plate, a pair of stacked reciprocal rotators, a Faraday rotator, and a reflector positioned in tandem adjacent to the birefringent plate. In a forward (transmitting) direction, a light wave signal exiting an optical fiber is split into a pair of orthogonal rays by the birefringent plate. The orthogonal rays then pass through a first reciprocal rotator and the Faraday rotator, which provides 22.5° of rotation. The rotated rays are then redirected by the reflector back though the Faraday rotator. After passing through the second reciprocal rotator, the orthogonal rays re-enter the same birefringent plate where they are recombined and launched in an output fiber. Since a Faraday rotator is a non-reciprocal device, any signal traveling through the isolator in the reverse (isolation) direction will be split on both passes through the birefringent plate such that neither will intercept the input fiber.

An isolated optical coupler is disclosed in U.S. Pat. No. 5,082,343 issued Jan. 21, 1992 in the name of Coult et al. The coupler described in the patent is comprised of a pair of lenses having a wavelength selective device and an isolator disposed therebetween. Another optical isolator, which attempts to improve upon Coult's design, is described in U.S. Pat. No. 5,594,821 issued in the name of Yihao Cheng.

Yet another optical isolator is described in U.S. Pat. No. 5,267,078 issued in the name of Shiraishi et al.

Although these prior art devices appear to provide their intended function of isolating in a unidirectional manner, substantially preventing light from propagating in a backward direction, while only allowing light to pass in a forward direction, it is an object of the present invention to provide a wavelength dependent isolator that in one mode of operation allows a first group of periodic wavelengths to pass in a first direction from a first port to a second port, while substantially preventing a second group of periodic wavelengths to pass, and simultaneously allowing a second group of wavelengths to pass in a second direction from the second port to the first port while substantially preventing the first group of wavelengths from passing in the same direction.

It is another object of this invention to provide a two-port isolator having a comb filter response that is different in one direction than the other.

Unlike prior art optical isolators generally used to allow signals to propagate in a forward direction but not in a backward direction, the isolator in accordance with an embodiment of this invention allows propagation of signals through the isolator in both directions from a first to a second port and vice versa, wherein propagation is wavelength dependent and mutually exclusive with respect to wavelengths that are able to pass in each direction.

SUMMARY OF THE INVENTION

Accordingly, the present invention relates to a bi-directional isolator comprising:

a first port for launching a first optical signal comprising at least one wavelength channel from a first set of wavelength channels, and for outputting a second optical signal comprising at least one wavelength channel from a second set of wavelength channels, independent of the first set of wavelength channels;

a second port for launching the second optical signal, and for outputting the first optical signal;

first routing means for directing the first optical signal from the first port to the second port, while preventing signals comprising at least one wavelength channel from the second set of wavelength channels from passing thereto; and

second routing means for directing the second optical signal from the second port to the first port, while preventing signals comprising at least one wavelength channel from the second set of wavelength channels from passing thereto.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings in which like reference numerals refer to similar elements, wherein:

FIG. **1** is a conceptual illustration of a bi-directional wavelength interleaving isolator;

FIGS. **2***a* and **2***b* illustrate one embodiment of a bi-directional wavelength interleaving isolator;

FIGS. **3***a* and **3***b* illustrate another embodiment of a bi-directional wavelength interleaving isolator;

FIG. **4** illustrates another embodiment of a bi-directional wavelength interleaving isolator;

FIG. **5** illustrates an embodiment of a two stage bi-directional wavelength interleaving isolator;

FIG. **6** is a polarization plot for the isolator of FIG. **5**;

FIGS. **7***a* and **7***b* illustrate another embodiment of a two stage bi-directional wavelength interleaving isolator;

FIG. **8** illustrates another embodiment of a two stage bi-directional wavelength interleaving isolator;

FIG. **9** illustrates another embodiment of a two stage bi-directional wavelength interleaving isolator;

FIG. **10***a* illustrates a top view of another embodiment of a two stage bi-directional wavelength interleaving isolator;

FIG. **10***b* illustrates a side view of the two stage bi-directional wavelength interleaving isolator of FIG. **10***a;*

FIG. **11** is a polarization plot for the isolator of FIGS. **10***a* and **10***b;*

FIG. **12***a* illustrates a top view of a folded bi-directional wavelength interleaving isolator having a quarter wave mirror;

FIG. **12***b* illustrates a side view of the isolator of FIG. **12***a;*

FIG. **13***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator having a quarter wave mirror;

FIG. **13***b* illustrates a side view of the isolator of FIG. **13***a;*

FIG. **14***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator having a quarter wave mirror;

FIG. **14***b* illustrates a side view of the isolator of FIG. **14***a;*

FIG. **15***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator having a reflecting prism;

FIG. **15***b* illustrates a side view of the isolator of FIG. **15***a;*

FIG. **16** illustrates another embodiment of a folded bi-directional wavelength interleaving isolator with a polarization plot of the even channels; and

FIG. **17** illustrates the bi-directional wavelength interleaving isolator of FIG. **16** with a polarization plot of the odd channels.

DETAILED DESCRIPTION

Bi-directional wavelength interleaving optical isolators provide the ability to pass a first set of optical signals (e.g., ITU even channels) from a first port to a second port. The bi-directional wavelength interleaving optical isolators also pass a second set of optical signals (e.g., ITU odd channels) from the second port to the first port. Thus, the bi-directional wavelength interleaving optical isolator can provide bi-directional communications by passing a first set of signals in a first direction and a second set of signals in a second direction.

FIG. **1** is a conceptual illustration of a bi-directional wavelength interleaving isolator. The isolator of FIG. **1** passes optical signals having a first set of frequencies (e.g., 1920.00, 1920.50, 1921.00, 1921.50, . . . 1960.00×100 GHz) in a first direction and optical signals having a second set of frequencies (e.g., 1920.25, 1920.75, 1921.25, . . . 1960.25×100 GHz) in the other direction. Thus, the isolator of FIG. **1** is a bi-directional device.

FIGS. **2***a* and **2***b* illustrate the simplest embodiment of the bi-directional isolator according to the present invention through which even channel signals can pass from a first port **1** to a second port **2**, and odd channel signals can pass from the second port **2** to the first port **1**. Lenses **8***a* and **8***b*, preferably graded index (GRIN) lenses, collimate incoming beams and focus outgoing beams to and from suitable waveguides. A first polarization-dependent beam director is in the form of a walk-off crystal **10**, which splits incoming beams into orthogonally polarized sub-beams **12***a* and **12***b* (FIG. **2***a*) or combines orthogonally polarized sub-beams **11***a* and **11***b* (FIG. **2***b*) for output. The first beam director **10** directs the sub-beams through a birefringent assembly **13**, which is comprised of two elements **14***a* and **14***b* of birefringent material such as thick waveplates having their axes of polarization diversity oriented differently. The fast and slow axes of the two elements are arranged such that they are purposefully misaligned to provide a substantially flat-top periodic wavelength output response that corresponds to a desired comb filter response. In a preferred embodiment the first block **14***a* is half the length (e.g. length L=c/(2×FSR)) of the second block **14***b* (e.g. length 2L) and is oriented at 45° to vertically polarized incoming light, while the second block **14***b* is oriented at 105° to the vertically polarized incoming light. In the illustrated embodiment, the birefringent assembly is adapted to have no cumulative effect on the polarization of the even number channels (see FIG. **2***a*), while rotating the polarization of the odd number channels by 90° (see FIG. **2***b*), i.e. the birefringent assembly is a wavelength selective polarization rotator. A birefringent assembly is the preferred means to provide the interleaving function; however, it is possible to use other forms of interleavers, e.g. Fabry-Perot or Gires-Tournois etalon based, to provide the necessary wavelength selective polarization rotation.

A non-reciprocal rotator **16** is also positioned in the path of the sub-beams **11***a*, **11***b*, **12***a* and **12***b*. The non-reciprocal rotator **16** is preferably comprised of a Faraday rotator and a half wave plate, which combine to rotate the polarization of sub-beams traveling in one direction by 90°, while having no cumulative effect on the polarization of the sub-beams traveling in the opposite direction. In the illustrated embodiment, the polarization of signals, i.e. the even number channels, traveling from the first port **1** to the second port **2** is rotated by 90°; while the polarization of signals, i.e. the odd number channels, traveling from the second port **2** to the first port **1** is unchanged.

A second polarization-dependent beam director in the form of a walk-off crystal **18** is optically coupled to the non-reciprocal rotator **16** for combining orthogonally polarized sub-beams **12***a* and **12***b* (FIG. **2***a*) for output via lens **8***b*, and for separating a beam input the second port **2** into orthogonally polarized sub-beams **11***a* and **11***b* (FIG. **2***b*). Walk-off crystal **18** is similar to walk-off crystal **10**, except that it is reversed and inverted, whereby it combines orthogonally polarized sub-beams for output along a path that is parallel to the original input path.

With this arrangement, a signal with even number channels, input the first port **1** along a first path **20**, is initially split into two orthogonally polarized sub-beams **12***a* and **12***b*, which travel along the first path **20** and a second path **21**, respectively. The two sub-beams **12***a* and **12***b* are directed through the birefringent assembly **13**, which has no effect on their polarization, and through the non-reciprocal rotator **16**, which rotates their polarization by 90°. Accordingly, the second beam director **18** combines the sub-beams **12***a* and **12***b* for output the second port **2** along the second path **21**. If an input signal containing any odd number channels is launched via the first port **1**, the polarization of these channels will be rotated by both the birefringent assembly **13** and the non-reciprocal rotator **16**, whereby the second beam director **18** will disperse these channels away from the second port **2**.

FIGS. **3***a* and **3***b* illustrate another embodiment of a bi-directional isolator according to the present invention, in which a half wave plate **22** is positioned to rotate the polarization of sub-beam **12***b*, whereby both sub-beams **12***a* and **12***b* have the same polarization entering the birefringent assembly **13**, and whereby sub-beams **11***a* and **11***b* have orthogonal polarizations entering walk-off crystal **10**. Moreover, a half wave plate **23** is positioned to rotate the polarization of sub-beams **11***a*, whereby both of the sub-beams **11***a* and **11***b* have the same polarization entering the birefringent assembly **13**, and whereby sub-beams **12***a* and **12***b* have orthogonal polarizations entering walk-off crystal **18**. To compensate for this added rotation, the non-reciprocal rotator **16** is reversed so that the polarization of sub-beams passing from the first port **1** to the second port **2** is not effected any further, while an additional rotation of 90° is added to sub-beams traveling from the second port **2** to the first port **1**. Accordingly, the non-reciprocal rotator **16** and the wave plates **22** and **23** combine to provide the same non-reciprocal rotation as the previous embodiment.

FIG. **4** illustrates another embodiment of a bi-directional isolator according to the present invention, in which wave plates **41**, **42** and **43** are provided to re-orient the sub-beams before entering the birefringent elements **14***a* and **14***b*, rather than having the birefringent elements **14***a* and **14***b* oriented at different angles. Moreover, the second element **14***b* is comprised of two similar components **44** and **45**, which are both similar to birefringent element **14***a*. Tuning plates **46** are also provided for fine-tuning the orientations of the sub-beams. This embodiment also discloses another non-reciprocal rotator arrangement, which includes a Faraday rotator **48** in combination with two half-wave plates **50** and **51** mounted between the walk-off crystal **10** and the birefringent assembly **13**, and a half-wave plate **52** mounted between the birefringent assembly **13** and the walk-off crystal **18**. The wave plate **50** and the Faraday rotator **48** are oriented to rotate the polarization of a sub-beam, e.g. **11***a*, traveling from the first port **1** to the second port **2** by 90°, while leaving the polarization of a sub-beam, e.g. **12***a*, traveling from the second port **2** to the first port **1**, unaffected. However, the wave plate **51** and the Faraday rotator **48** are oriented to rotate the polarization of a sub-beam, e.g. **12***b*, traveling from the second port **2** to the first port **1**, while unaffecting the polarization of a sub-beam, e.g. **11***b*, traveling in the opposite direction. The wave plate **52** is required to provide the polarization rotation for the sub-beam **12***b* traveling from the first port **1** to the second port **2**, while canceling the polarization rotation provided by the combination of wave plate **51** and Faraday rotator **48** to sub-beam **11***b* traveling from the second port **2** to the first port **1**.

As is evident from FIGS. **2**, **3** and **4**, it is possible to design many different waveplate arrangements in combination with a Faraday rotator (or other non-reciprocal device) to provide the necessary non-reciprocal rotation.

FIG. **5** illustrates an embodiment of a two-stage bi-directional wavelength interleaving isolator. For the description that follows, odd ITU channels are passed from a first port **200** to a second port **290**, and even ITU channels are passed from the second port **290** to the first port **200**. Even and odd ITU channels can be passed in the opposite directions and/or other frequency sets can be passed as described.

A set of odd channels is received via port **200**. In one embodiment, port **200** is a collimator assembly having a graded index (GRIN) lens **202** to collimate light launched from a suitable waveguide **203**, an end of which is surrounded by ferrule **204**. Other types of lenses can also be used, or pre-collimated light can be received. Port **200** is optically coupled to first beam director in the form of a first walk-off crystal **205**.

The first walk-off crystal **205** operates to separate the ordinary and the extraordinary components of an incoming optical signal. The spatially separated optical signals emerging from the first walk-off crystal **205** are a vertical component **211***a* and a horizontal component **211***b* of the optical signal received via port **200**.

The vertical component **211***a* passes through a half wave plate **210** and a garnet plate (Faraday rotator) **220**, which combine to rotate the polarization of the component **211***a* from vertical to horizontal. The horizontal component **211***b* passes through the garnet plate **220** and a half wave plate **215**, which is oriented to cancel the rotation of the garnet plate **220** for beams traveling from the first port **200** to the second port **290**. Accordingly, both components **211***a* and **211***b* have the same polarization entering a first stage **222** of a birefringent assembly **224**, e.g. horizontal.

Initially, the components **211***a* and **211***b* of the optical signal are directed to a first birefringent filtering element **230** of the first stage **222**. In the illustrated embodiment, a half wave plate **225** and a tuning plate **227** are used to orient the sub-beams for entry into the first birefringent filtering element **230** to provide the desired filtering function. The first birefringent element **230** can be composed of multiple birefringent crystals that are selected to provide improved thermal stability over a range of operating temperatures as compared to a single birefringent crystal. In one embodiment, one crystal is a TiO_2 crystal and a second crystal is a YVO_4 crystal; however, other crystal types can also be used. Other birefringent assemblies can also be used, for example, a single crystal can be used if temperature stability is not important.

The thickness of tuning plate **227** is selected to provide the desired frequency offset in order to tune the circulator to provide the desired frequency response. Preferably, the tuning plate **227** is quartz (SiO_2); however, other materials can also be used. In an embodiment where the crystals of birefringent element **230** are normal to the optical path, walk-off effects that are caused by angle tuning are reduced or eliminated.

A second filtering element **252** has an optical path length of 2L, and includes birefringent crystals **236** and **238**, each of which is similar to the first birefringent element **230**. Tuning plates **234** and **240**, and half wave plates **232** and **242** are arranged to orient and tune the components **211***a* and **211***b* in a similar manner as the tuning plate **227** and half wave plate **225**. In the illustrated embodiment, the first stage **222** is designed to rotate the polarization of the odd numbered channels, while having no cumulative effect on the even numbered channels. Accordingly, the previously horizontally polarized odd numbered channels will become vertically polarized, while any unwanted even numbered channel signals will remain horizontally polarized.

A polarizer **244** positioned after the first stage **222** ensures that only light of a predetermined polarization, e.g. vertically polarized, passes therethrough to provide the desired filtering characteristics. For any even channels that are launched through the first port **1**, the polarizer acts to scatter these unwanted signals.

A second stage **243** of the birefringent assembly **224** is comprised of a third birefringent filtering element **254** and a fourth birefringent element **256**, which are arranged in a similar manner as the first and second birefringent filtering elements **230** and **252**, respectively. Preferably, the third birefringent filtering element **254** has an optical path length of L, while the fourth birefringent filtering element **256** is comprised of two birefringent crystals **266** and **268**, each having an optical path length of L. As above, a half wave plate **246** and a tuning plate **248** are used to orient the components **211***a* and **211***b* before entering the third birefringent filtering element **254**. Moreover, half wave plates **262** and **272**, and tuning plates **264** and **270** are used to orient the components **211***a*, **211***b*, **212***a* and **212***b* before entering the fourth birefringent filtering elements **256**.

The optical signal components comprising the odd numbered channels that emerge from the fourth filtering element **256** will, again, have had their state of polarization rotated by passage through the second stage **243**, e.g. from vertical to horizontal. One of the components **211***a* passes through a garnet plate (Faraday rotator) **275** and a half wave plate **283**, which are oriented to rotate the polarization of the component **211***a* in opposite directions, thereby having no cumulative effect. The other component **211***b* passes through the garnet plate **275** and a half wave plate **280**, which are oriented to rotate the polarization of the component **211***b* in the same direction, thereby rotating the polarization by 90°. A second beam director, preferably in the form of a second walk-off crystal **285**, spatially recombines the optical components **211***a* and **211***b* and directs the combined optical components to the second port **290**. As in the previous embodiments, the second walk-off crystal **285** is reversed and inverted relative to the first walk-off crystal **205**, thereby combining and directing only the desired components with the designated polarizations. Any signals or channels that do not have the designated polarization and spatial position will be isolated from the second port **290**. The second port **290** is comprised of a lens **291** and a ferrule **292**, which surrounds an end of a suitable waveguide **293**.

Even ITU channels passing from port **290** to port **200** are processed in the reverse manner, except for the fact that the birefringent filtering elements have no cumulative effect on their state of polarization. Accordingly, only the garnet plates **220** and **275** along with the half wave plates **210**, **215**, **280** and **283**, which combine to provide non-reciprocal polarization rotators, effect the polarization of the components

In one embodiment, filtering elements **230**, **252**, **254** and/or **256**, or one or more components of filtering elements **230**, **252**, **254** and/or **256**, are angled a small amount (e.g. 1° to 3°) from normal with respect to the signals. The angle reduces reflection that can cause interference.

FIG. **6** are polarization plots for the isolator of FIG. **5**. The layout of the isolator of FIG. **5** is provided for reference purposes. The top row of polarization plots corresponds to a set of signals passing from the first port **200** to the second port **290**. The bottom row of polarization plots corresponds to a set of signals passing from the second port **290** to first port **200**.

Polarization plot **300** illustrates an optical signal having both horizontal and vertical components representing the collimated beam that emerges from port **200**. Polarization plot **305** illustrates the spatial separation of the horizontal and vertical components **211***a* and **211***b* provided by walk-off crystal **205**.

Polarization plot **310** illustrates the components of the optical signal both having a horizontal polarization upon emerging from garnet **220**. Birefringent filtering elements **230** and **252** provide filtering of the optical signal, which results in two beams, each of which includes horizontal (unwanted even channels) and vertical components. Polarization plot **315** illustrates the polarizations of the components upon emerging from filtering element **252**.

Polarization plot **320** illustrates the components of the optical signal after passing through polarizer **244**, which scatters the horizontally polarized light and results in both component beams having only vertically polarized light.

Polarization plot **325** illustrates the components of the optical signal after passing through filtering element **256**. Filtering elements **254** and **256** provide filtering of the optical signal and results in the two beams having a horizontal polarization.

Polarization plot **330** illustrates the polarization of the components upon emerging from half wave plates **280** and **283**. At this point, one component has a horizontal polarization and the other component has a vertical polarization.

Polarization plot **335** illustrates the combined optical signal having both horizontal and vertical components as a result of walk-off crystal **285** combining the horizontal and vertical components of the optical signal. The combined optical signal, e.g. comprising only odd numbered channels, is directed to the second port **290**.

Polarization plot **350** illustrates an optical signal having both horizontal and vertical components representing the collimated beam that emerges from the second port **290**.

Polarization plot **355** illustrates the spatial separation of the horizontal and vertical components **212***a* and **212***b* provided by walk-off crystal **285**.

Polarization plot **360** illustrates the components of the optical signal both having a vertical polarization upon emerging from garnet **275**.

Filtering elements **256** and **254** provide filtering of the optical signal, which results in two beams, each of which include horizontal and vertical components. Polarization plot **365** illustrates the two beams each having horizontal (unwanted) and vertical components.

Polarization plot **370** illustrates the components of the optical signal after passing through polarizer **244**, which scatters the horizontally polarized light and results in both component beams **212***a* and **212***b* having only vertically polarized light. Polarization plot **375** illustrates the components of the optical signal after passing through filtering elements **252** and **230**. Filtering elements **252** and **230** provide filtering of the optical signal, which results in the two beams still having a vertical polarization.

Polarization plot **380** illustrates the polarization of the components upon emerging from half wave plates **210** and **215**. At this point, one component is vertically polarized and the other component is horizontally polarized.

Polarization plot **385** illustrates the combined optical signal, which comprises only even numbered channels, having both horizontal and vertical components as a result of walk-off crystal **205** combining the horizontal and vertical components of the optical signal. The combined optical signal is directed to the first port **200**.

FIGS. **7***a* and **7***b* illustrate another embodiment of a two-stage bi-directional wavelength interleaving isolator, which is similar to the embodiment of FIG. **5**, except that the individual birefringent elements **230**, **252**, **254** and **256** are, themselves, oriented at the appropriate angles (e.g. 45° and 105°) relative to the incoming beams, thereby eliminating the need for wave plates **225**, **232**, **242**, **246**, **262** and **272**. Moreover, the garnet plate and wave plate arrangement that makes the device non-reciprocal is slightly different to ensure that the process is dispersion free. With reference to FIG. 7*a*, a half wave plate **291** is positioned in the path of one of the components, e.g. the extraordinary component of the input light, so that both components have the same polarization entering the first filtering stage **222**. A first non-reciprocal rotator **292**, which comprises a Faraday rotator and a half wave plate, is positioned between the first filtering stage **222** and the polarizer **244**. The first non-reciprocal rotator has no effect on the polarization of the light traveling from the first port **200** to the second port **290**. An additional half wave plate **293** is positioned between the first filtering stage **222** and the second filtering stage **243** in the path of both components of the input light to ensure that the polarization of both components entering the second filtering stage **243** is orthogonal to their polarization entering the first filtering stage **222**, which will eliminate chromatic dispersion. A second non-reciprocal rotator **294**, working in reverse to the non-reciprocal rotator **292**, along with a half wave plate **295** are positioned between the second filtering stage **243** and the second beam directing walk-off crystal **285** for manipulating the polarization of the components, whereby they are combined and output the second port **290**.

In the illustrated embodiment, even channel sub-beams are transmitted from the first port **200** to the second port **290**, after undergoing three polarization rotations of 90°, i.e. in the half wave plate **293**, in the non-reciprocal rotator **294**, and in the combination of the half-wave plates **291** and **295**. When traveling from the second port **290** to the first port **200**, the odd channel sub-beams undergo five polarization rotations, i.e. in the second filtering stage **243**, in the half wave plate **293**, in the first non-reciprocal rotator **292**, in the first filtering stage **222**, and in the combination of the half wave plates **295** and **291**.

FIG. **8** illustrates another embodiment of a two-stage bi-directional wavelength interleaving isolator. The isolator of FIG. **8** operates in the same manner as the isolator of FIG. **5**, except that the polarizer **244** of FIG. **5** is replaced by a polarization beam splitter (PBS) **400**, which acts to reflect, i.e. spill off or scatter, the unwanted even channel signals traveling from the first port **200** to the second port **290**, and the unwanted odd channel signals traveling from the second port **290** to the first port **200**.

FIG. **9** illustrates another embodiment of a two-stage bi-directional wavelength interleaving isolator in which the polarizer **244** of FIG. **5** or the PBS of FIG. **8** is replaced by a walk-off crystal **500** for dispersing the unwanted signals.

FIG. **10***a* illustrates a top view of another embodiment of a two-stage bi-directional wavelength interleaving isolator. FIG. **10***b* illustrates a side view of the bi-directional wavelength interleaving isolator of FIG. **10***a*. For the description that follows, odd ITU channels are passed from port **600** to port **690**. Even ITU channels are passed from port **690** to port **600**. Even and odd ITU channels can be passed in the opposite directions and/or other frequency sets can be passed as described.

An optical signal carrying a set of odd channels are received via port **600**. The signal is passed to a first walk-off crystal **605**, which provides spatial separation between the vertical and the horizontal components of the signal. The components of the signal are passed through half wave plate **610** and garnet plate **615** to a first filtering stage **620** of a birefringent filtering assembly.

In one embodiment, the first filtering stage **620** includes half wave plate and/or tuning plate **630**, first birefringent element **632**, half wave plate and/or tuning plate **634**, a second birefringent element (comprised of birefringent crystals **635** and **636**), and half wave plate and/or tuning plate **638**. A second walk-off crystal **640** combines the horizontal and vertical components of the optical signal that emerge from the first filtering stage **620**.

The combined signal from the second walk-off crystal **640** is passed through half wave plate **650**. A third walk-off crystal **655** spatially separates the horizontal and vertical components of the optical signal that emerge from half wave plate **650**. The components of the optical signal are passed through a second filtering stage **625**.

In one embodiment, the second filtering stage **625** includes half wave plate and/or tuning plate **660**, a third birefringent element **662**, a half wave plate and/or tuning plate **664**, a fourth birefringent element (comprised of a birefringent crystals **666** and **668**), and a half wave plate and/or a tuning plate **670**. The optical signal that emerges from the second filtering stage **625** is passed through a garnet plate **675** and a half wave plate **680** to a fourth walk-off crystal **685**. The fourth walk-off crystal **685** spatially recombines the optical components and directs the combined optical components to the second port **690**. Even ITU channels passing from port **690** to port **600** are processed in the reverse manner.

In one embodiment, filtering stages **620** and/or **625**, or one or more components of filtering stages **620** and/or **625**, are angled a small amount (e.g. 1° to 3°) from normal with respect to the signals. The angle reduces reflection that can cause interference.

FIG. **11** is a polarization plot for the isolator of FIGS. **10***a* and **10***b*. The layout of the isolator of FIG. **10***a* is provided for reference purposes. The top row of polarization plots corresponds to a set of signals passing from port **600** to port **690**. The bottom row of polarization plots corresponds to a set of signals passing from port **690** to port **600**.

Polarization plot **700** illustrates an optical signal having both horizontal and vertical components representing the collimated beam that emerges from port **600**.

Polarization plot **705** illustrates the spatial separation of the horizontal and vertical components provided by the first walk-off crystal **605**. The broken lines representing unwanted even channels.

Polarization plot **710** illustrates the components of the optical signal having horizontal and vertical polarizations upon emerging from the wave plate **610** and the garnet **615**, which has no effect on their state of polarization.

The first filtering stage **620** provides filtering of the optical signal, and wavelength selective polarization rotation resulting in the two components each having horizontal and vertical components, i.e. the odd numbered channels have been rotated, while the even numbered channels have not.

Polarization plot **715** illustrates the polarizations of the signals upon emerging from the first filtering stage **620**.

Polarization plot **720** illustrates the components of the optical signal after passing through the second walk-off crystal **640**, which combines the odd channel components together, while leaving the unwanted even channel signals spatially separated.

Polarization plot **725** illustrates the polarizations of the components of the optical signal after passing through half wave plate **650** and the third walk-off crystal **655**, which rotates the polarization of all of the components and spatially separates the vertically polarized components from the horizontally polarized components, thereby scattering the unwanted signals from the correct path.

Polarization plot **730** illustrates the components of the optical signal after passing through the second filtering stage **625**. The second filtering stage **625** provides filtering of the optical signal and wavelength selective polarization rotation, resulting in the odd numbered channels undergoing a polarization rotation, while the even numbered channels remain the same polarization.

Polarization plot **735** illustrates the polarization of the components upon emerging from garnet **675** and half wave plate **680**, which have no cumulative effect on the polarization of the components.

Polarization plot **740** illustrates a combined optical signal, comprised of odd numbered channels, having both horizontal and vertical components as a result of the fourth walk-off crystal **685** combining the horizontal and vertical components of the optical signal. The combined optical signal is directed to port **690**, while the unwanted even numbered channels are directed elsewhere.

Polarization plot **750** illustrates an optical signal having both horizontal and vertical components representing the collimated beam that emerges from port **690**.

Polarization plot **755** illustrates the spatial separation of the horizontal and vertical components provided by the fourth walk-off crystal **685**.

Polarization plot **760** illustrates the components of the optical signal upon emerging from the wave plate **680** and the garnet **675**, which rotate the polarization of the components by 90°.

The second filtering stage **625** provides filtering of the optical signal, and rotates the polarization of the odd numbered channels, while leaving the even numbered channels unaffected, which results in two beams, each of which includes horizontal and vertical components. Polarization plot **765** illustrates the two beams each having horizontal and vertical components, as well as unwanted odd numbered channel signals (broken lines) and the even number channels.

Polarization plot **770** illustrates the components of the optical signal after passing through the third walk-off crystal **655** and the half wave plate **650**, which rotates the polarization of all of the components and spatially separates the vertically polarized components from the horizontally polarized components in a first direction, e.g. the x direction.

Polarization plot **775** illustrates the polarizations of the components of the optical signal after passing through the second walk-off crystal **640**, which spatially separates the vertically polarized components from the horizontally polarized components in a second direction perpendicular to the first direction, e.g. the y direction.

Polarization plot **780** illustrates the components of the optical signal after passing through the first filtering stage **620**, which provides filtering of the optical signal and selectively rotates the polarization of the odd numbered channels, while leaving the even numbered channels unaffected. Accordingly, the first filtering stage **620** only affects the polarization of the unwanted odd numbered channels shown in broken lines.

Polarization plot **785** illustrates the polarization of the components upon emerging from half wave plate **610** and garnet **615**, which, in this direction, rotates the polarization of all of the components by 90°.

Polarization plot **790** illustrates a combined optical signal having both horizontal and vertical components as a result of the first walk-off crystal **605** combining the horizontal and vertical components of the optical signal. The combined optical signal, which is comprised of even numbered channels, is then directed to the first port **600**.

FIG. **12***a* illustrates a top view of one embodiment of a folded bi-directional wavelength interleaving isolator, while FIG. **12***b* illustrates a side view of the isolator of FIG. **12***a*. For the description that follows, odd ITU channels are passed from port **800** to port **890**, while even ITU channels are passed from port **890** to port **800**. Even and odd ITU channels can be passed in the opposite directions and/or other frequency sets can be passed as described.

An optical signal carrying a set of odd channels is received via port **800**. The signal is passed to a first walk-off crystal **805**, which provides spatial separation between the vertical and the horizontal component sub-beams of the signal. The components sub-beams of the signal are passed through a half wave plate **810** and a garnet plate **815** to a birefringent filtering assembly **825**. The half wave plate **810** and the garnet plate **815** rotate the polarization of the component sub-beams by an equal amount in opposite directions resulting in no cumulative change to their polarization.

In this embodiment, a half wave plate and/or tuning plate **830** orients the component sub-beams in proper alignment for input into a first birefringent element **832**. A half wave plate and/or tuning plate **834** re-orient the component sub-beams for input into the second birefringent element, which is comprised of birefringent crystals **836** and **838**. Since the component sub-beams entered the birefringent assembly **825** with orthogonal polarizations, a tuning plate **840** and half wave plates **842** and **844** are used to rotate the polarization of the component sub-beams in opposite directions so that they have the same polarization upon entry into walk-off crystal **850**.

The component sub-beams from walk-off crystal **850** are directed through quarter wave plate **860** to mirror **870**, which reflects the signals back through quarter wave plate **860**. The double pass through the quarter wave plate **860** results in the sub-beams undergoing a polarization rotation of 90°. Accordingly, when the component sub-beams enter the walk-off crystal **850** for the second time, they get walked off, and exit the walk-off crystal along a path separate and parallel to the original path. A second pass through the birefringent filtering assembly results in the polarization of the component sub-beams being rotated by 90°. To minimize the size of the birefringent assembly **825**, a reflective prism **820** is used to direct the component sub-beams to the second port **890**. To minimize dispersion, the polarization of the component sub-beams is rotated by 90° by passing them through a garnet plate **880** and a half wave plate **882**, before a walk-off crystal **885**. The walk-off crystal **885** spatially recombines the components of the optical signals and directs the combined signal to the second port **890**. Even ITU channels passing from port **690** to port **600** are processed in the reverse manner, except the birefringent assembly has no effect on the polarization.

In one embodiment, the birefringent filtering assembly **825**, or one or more components of the birefringent filtering assembly **825**, are angled a small amount (e.g. 1° to 3°) from normal with respect to the signals. The angle reduces reflection that can cause interference.

FIG. **13***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator. FIG. **13***b* illustrates a side view of the isolator of FIG. **13***a*. The isolator of FIGS. **13***a* and **13***b* operates in a similar manner as the isolator of FIGS. **12***a* and **12***b*, except that the half wave plates **842** and **844** are replaced by a single half wave plate **952**, and the single half wave plate **830** is replaced by a pair of oppositely oriented half wave plates **930** and **932**. This arrangement enables both component sub-beams to have the same polarization when entering the birefringent assembly **825**.

FIG. **14***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator. FIG. **14***b* illustrates a side view of the isolator of FIG. **14***a*. The isolator of FIGS. **14***a* and **14***b* operate in a similar manner as the isolator of FIGS. **12***a* and **12***b* and of FIGS. **13***a* and **13***b*, except that the half wave plate **810** is replaced by a pair of oppositely oriented half wave plates **1000** and **1005**, and half wave plate **882** is replaced by two oppositely oriented half wave plates **1080** and **1085**. Moreover, half wave plates **830** and **952** are provided at either end of the birefringent assembly, respectively. The waveplate pairs, i.e. **1000** and **1005**, and **1080** and **1085**, are oppositely oriented so that, in combination with the garnet plate **810**, they rotate the polarization of one of the component sub-beams passing in one direction, while rotating the polarization of the other component sub-beam in the other direction.

For the description that follows, odd ITU channels are passed from port **800** to port **890**, and even ITU channels are passed from port **890** to port **800**. Even and odd ITU channels can be passed in the opposite directions and/or other frequency sets can be passed as described.

An optical signal carrying a set of odd channels are received via port **800**. The signal is passed to walk-off crystal **805**, which provides spatial separation between the ordinary and the extraordinary components of the signal. The extraordinary component **801** of the signal is passed through quarter wave plate **1000** and garnet plate **1010**, which are oriented to rotate the polarization of the extraordinary component **801** by equal amounts, but in opposite directions resulting in no cumulative change. The ordinary component **802** is passed through half wave plate **1005** and garnet plate **810**, which are oriented to rotate the polarization of the ordinary component **802** by 90°. Accordingly, both components **801** and **802** are launched through the birefringent assembly **825** in the same polarization state, e.g. extraordinary.

Since the birefringent assembly **825** is designed to rotate the polarization of the odd ITU channels, the components **801** and **802** enter the walk-off crystal **850** as ordinary sub-beams, and therefore pass directly therethrough. Two passes through the quarter wave plate **860** results in the sub-beams becoming extraordinary and being walked off by the walk-off crystal **850**, see FIG. **14***b*. The extraordinary sub-beams exit the walk-off crystal **850** and enter the birefringent assembly **825** for a second pass along a path parallel to the path taken during the first pass. Again, the birefringent assembly **825** rotates the polarization of the sub-beams, whereby they become ordinary. The reflective prism **820** directs the sub-beams towards the second port **890**; however, one of the sub-beams **802** passes through the half wave plate **1080** and the garnet plate **880**, which combine to rotate the polarization of the sub-beam by 90°. The other sub-beam **801** passes through the half wave plate **1085** and the garnet plate **880**, which combine to have no cumulative effect on the polarization thereof. The, now, orthogonal sub-beams **801** and **802** are combined in the walk-off crystal **885** for output the second port **890**.

Even ITU channels passing from the second port **890** to the first port **800** are processed in the reverse manner, except that the birefringent assembly **825** has no effect on the polarization thereof. Initially, the half wave plate **1085**, in combination with the garnet plate **810**, ensures that both even channel sub-beams are extraordinary. Passage through the birefringent assembly **825** does not affect the polarization of the sub-beams, whereby the walk-off crystal **850** directs them towards the half wave plate **860** and the path to the first port **800**. The polarization rotation provided by the double passage through the half wave plate **860** enable the walk-off crystal **850** to pass the even channel sub-beams (now ordinary) directly therethrough for a second pass through the birefringent assembly **825**. In the opposite direction half wave plate **1000** and garnet plate **810** combine to rotate the polarization of one of the even channel sub-beams by 90°, whereby the pair of even channel sub-beams can be combined in walk-off crystal **805** for output the first port **800**.

FIG. **15***a* illustrates a top view of another embodiment of a folded bi-directional wavelength interleaving isolator, which includes a reflecting prism **1110**. FIG. **15***b* illustrates a side view of the isolator of FIG. **15***a*. The isolator of FIGS. **15***a* and **15***b* operate in a similar manner as the isolator of FIGS. **14***a* and **14***b* except that the quarter wave plate **860** and mirror **870** are replaced by a polarizer **1100** and a reflecting prism **1110**, which re-directs the pair of sub-beams without changing their polarization.

FIG. **16** illustrates another embodiment of a folded bi-directional wavelength interleaving isolator, and in particular illustrates an example of the polarization states of the even ITU channel sub-beams as they propagate through the device. Launched through a first port **1200**, an even channel input beam is divided into two orthogonal sub-beams **1205** and **1210** by a walk-off crystal **1215**. A half wave plate **1220** is positioned in the path of the extraordinary sub-beam **1210** to ensure both sub-beams **1210** and **1205** have the same polarization, e.g. vertically polarized. A spacer **1222** is provided to facilitate assembly. The sub-beams **1210** and **1205** pass through a non-reciprocal rotator **1225**, which preferably comprises a Faraday rotator and a half wave plate. For sub-beams passing in this direction, the Faraday rotator and the half wave plate are oriented so that they have no effect on the polarization thereof. Subsequently, the sub-beams **1205** and **1210** pass through a birefringent assembly **1230**, preferably comprising a first birefringent element **1235** of length L oriented at an angle of 45° to the input sub-beams, and a second birefringent element **1240** of length 2L oriented at an angle of 105°. The birefringent assembly has no effect on the polarization of the even channel sub-beams, which then pass through another spacer **1245** into contact with a polarization beam splitting retro-reflective prism (PBSRRP) **1250**. The PBSRRP **1250** redirects only the vertically polarized sub-beams, while transmitting, i.e. spilling off or scattering, any unwanted horizontally polarized light. The sub-beams **1205** and **1210** are directed through a half wave plate **1255**, which rotates their polarization by 90°, e.g. from vertical to horizontal, whereby the sub-beams **1205** and **1210** enter the birefringent assembly for a second time with a polarization orthogonal to their polarization before the first pass. This eliminates any dispersion caused by passage through the birefringent assembly **1230**. Again, the birefringent assembly **1230** has no effect on the polarization of the even channel sub-beams **1205** and **1210**. However, in this direction, the non-reciprocal rotator **1225** rotates the polarization of the sub-beams **1205** and **1210** by 90°, e.g. from horizontal to vertical. A half wave plate **1260** is positioned in the path of sub-beam **1205** to ensure the sub-beams **1205** and **1210** are orthogonally polarized so that they can be combined in walk-off crystal **1265** and output the second port **1270**. The polarization of sub-beam **1205** is rotated to ensure that sub-beam **1205** follows the extraordinary path during the recombination, since it followed the ordinary path during the separation. Another spacer **1275** is provided to facilitate assembly.

FIG. **17** illustrates the device of FIG. **16**, and in particular illustrates an example of the polarization states of the odd ITU channel sub-beams as they propagate through the device. The odd channel sub-beams **1280** and **1285** travel from the second port **1270** to the first port **1200** in a similar same fashion as the even channel sub-beams **1205** and **1210**, except that their state of polarization is rotated by 90° each time they pass through the birefringent assembly **1230**. However, the half wave plate **1255** is positioned to rotate the polarization of the odd channel sub-beams back to vertical before they enter the PBSRRP **1250**, and the non-reciprocal rotator **1225** is positioned to rotate the polarization of the sub-beams back to vertical before one of them enters the half wave plate **1220**.

In the foregoing specification, the invention has been described with reference to specific embodiments thereof. It will, however, be evident that various modifications and changes can be made thereto without departing from the broader spirit and scope of the invention. The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense.

What is claimed is:

1. A bi-directional isolator comprising:

a first port for launching a first optical signal comprising at least one wavelength channel from a first set of wavelength channels, and for outputting a second optical signal comprising at least one wavelength channel from a second set of wavelength channels, independent of the first set of wavelength channels;

a second port for launching the second optical signal, and for outputting the first optical signal;

first routing means for directing the first optical signal from the first port to the second port, while preventing signals comprising at least one wavelength channel from the second set of wavelength channels from passing thereto; and

second routing means for directing the second optical signal from the second port to the first port, while preventing signals comprising at least one wavelength channel from the second set of wavelength channels from passing thereto.

2. The bi-directional isolator according to claim **1**, wherein the first routing means comprises:

wavelength selective polarization rotating means for rotating the polarization of the first set of wavelength channels, while having no substantial cumulative effect on the polarization of the second set of wavelength channels; and

first polarization-dependent beam directing means for directing the first optical signal towards the second port.

3. The bi-directional isolator according to claim **2**, wherein the second routing means comprises:

non-reciprocal polarization rotating means for rotating the polarization of the second optical signal, while having substantially no cumulative effect on the polarization of the first optical signal; and

second polarization-dependent beam directing means for directing the second optical signal towards the first port.

4. The device according to claim **2**, wherein the wavelength selective polarization rotating means comprises an interleaver.

5. The device according to claim **4**, wherein the interleaver is a birefringent crystal assembly.

6. The device according to claim **5**, wherein the birefringent crystal assembly comprises a first stage, which includes a first element of length L, and a second element of length 2L.

7. The device according to claim **6**, wherein the birefringent crystal assembly further comprises: a second stage, which includes a third element of length L, and a fourth element of length 2L; and

signal separating means between the first and second stages for separating wavelengths of the second set of wavelengths from the first signal, and for separating wavelengths of the first set of wavelengths from the second signal.

8. The device according to claim **7**, wherein the birefringent crystal assembly further comprises a polarization rotating means for ensuring that the first and second signals enter the second stage with a polarization orthogonal to their polarization when they entered the first stage.

9. The device according to claim **7**, wherein the signal separating means comprises a polarization beam splitting means selected from the group consisting of:

a polarizer, a polarization beam splitter (PBS) cube, a walk-off crystal, and a pair of walk-off crystals having orthogonal crystal axes with a half wave plate therebetween.

10. The device according to claim **5**, further comprising reflecting means for directing the first and second signals through the birefringent crystal assembly for a second pass.

11. The device according to claim **10**, wherein the reflecting means comprises a walk-off crystal for receiving the first and second signals from the birefringent crystal assembly along a first and a second path, respectively;

a quarter wave plate for rotating the polarization of the first and second signals; and

a mirrored surface for reflecting the first and second signals back through the quarter wave plate to the walk-off crystal;

whereby the first and second signals pass through the walk-off crystal a second time along the second and the first paths, respectively.

12. The device according to claim **10**, wherein the reflecting means comprises an angled prism with reflective coatings for directing the first signal traveling along a first path in one direction to a second path in another direction, and for directing the second signal traveling along the second path to the first path.

13. The device according to claim **12**, wherein the reflective coatings are polarization sensitive coatings.

14. The device according to claim **12**, wherein the angled prism is a right angled prism.

15. The device according to claim **10**, further comprising polarization rotating means for ensuring that the polarizations of the first and second signals entering the birefringent crystal assembly for the second pass are orthogonal to their polarizations prior to their first pass.

16. The device according to claim **1**, wherein the first set of wavelength channels comprises a first plurality of spaced wavelength channels having predetermined center wavelengths spaced by a predetermined channel spacing “d”; and

wherein the second set of wavelength channels comprises a second plurality of spaced wavelength channels having predetermined center wavelengths spaced by a predetermined channel spacing "d".

17. The device according to claim **16**, wherein the first set of wavelength channels comprises the odd numbered ITU channels; and

wherein the second set of wavelength channels comprises the even numbered ITU channels.

18. The device according to claim **3**, wherein the non-reciprocal polarization rotating means comprises a Faraday rotator and at least one reciprocal rotator.

19. The device according to claim **3**, wherein the first polarization-dependent beam directing means comprises a first walk-off crystal optically coupled to the first port for dividing the first signal into two sub-beams, and for combining two sub-beams of the second signal; and

wherein the second polarization-dependent beam directing means comprises a second walk-off crystal optically coupled to the second port for dividing the second signal into two sub-beams, and for combining the two sub-beams of the first signal.

20. The device according to claim **19**, wherein the second walk-off crystal is reversed and inverted relative to the first walk-off crystal.

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